Dynamics of knowledge base complexity: An inquiry into oil producing countries' struggle to build innovation capabilities

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Abstract:

According to conventional wisdom, the petroleum industry is classified as a ‘resource based’ and ‘mature’ industry. It is subject to the ‘resource curse’ thesis, exhausted of ‘technological opportunities’ with limited capacity for knowledge based economic growth. This study questions the adequacy of this line of reasoning. Exploring the technological complexity of the sector, a complementary argument is presented. We show that the sector has recently experienced a surge in ‘technological opportunities’. However the ‘systemic complexity of the knowledge base’ has constrained many oil producing countries’ enjoyment of these opportunities. This view highlights the role of dynamics of knowledge base complexity as an important ‘cognitive’ barrier for building innovation capabilities in endowed countries.

This study is based on the extension of a ‘Sectoral Innovation Systems’ approach, highlighting the role of technological regimes in catch-up possibilities and strategies. Knowledge base complexity is explored as an under-researched element of technological regimes. The research contributes in three ways. First, it introduces a dynamic and three-dimensional view of knowledge base complexity at the conceptual level, and hypothesizes its implication for patterns of innovation and catch-up processes. Second, a quantitative methodology is developed to examine the proposed hypotheses. Third, the conceptual and methodological suggestions are empirically examined in the context of upstream petroleum industry.

The findings propose that the sector has gone through phases of transformation and reconfiguration. The sector’s technological regime over the most recent period experienced high opportunities combined with rising systemic complexity of the knowledge base. We show that this trend in technological regimes is associated with shift of the sector from Schumpeter Mark I to II and with the emergence of major Integrated Service Companies as new system integrators coping with rising systemic complexity. We also observe that rising systemic complexity is associated with slow down and halt of geographical dispersion of innovation. The sector-wide cumulativeness stemming from systemic complexity creates high cognitive barriers to entry for latecomers. The very scarce examples of catch-up in a few advanced oil producing countries suggest that high innovation opportunities in complex industries are open mostly to countries with both advanced national innovation systems and accumulated production experience. For latecomer countries to benefit, their industrial policy needs to cope with increasing systemic complexity, mitigating its coordination costs and facilitating the integration of distributed catch-up processes. This highlights the key role of ‘late comer systems integrators’ for successful catch-up.

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Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to his or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed

Date

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Abbreviations

ADiv	Average Diversity
AMIC	Assignee's Main Invention Country
ASto	Average innovation Stock
C	Concentration
CFP	Compagnie Française des Pétroles
CNPC	China National Petroleum Corporation
CV	Coefficient of Variance
DC	Degree centrality
Div	Diversity
E&D	Exploration and Development
EPC	Engineering, Procurement, Construction
EPO	European Patent Office
F	Number of innovative firms
IA	Industry Architecture
IC	Inventor Country
ICT	Information and Communication Technology
IGC	International Geographical Concentration
ILC	Industry Life Cycle
IOC	International Oil Companies
IPC	International Patent Classification
IPF	International Patent Families
ISC	Integrated Service Companies
JPO	Japan Patent Office
KAP	Knowledge Accumulation Percentage
M&A	Mergers and Acquisition
N	Number of countries
NDC	Normalized Degree centrality
NE	Share of new entries
NOC	National Oil Companies
NIOC	National Iranian Oil Company
OPEC	Organization of the Petroleum Exporting Countries
PATSTAT	EPO Worldwide Patent Statistical Database
PCT	Paris Convention Treaty
PDVSA	Petróleos de Venezuela, S.A.
PIW	Petroleum Intelligence Weekly
PLC	Product Life Cycle
R&D	Research and Development
RTA	Revealed Technological Advantage
RV	Related Variety
SIS	Sectoral Innovation Systems

SNA	Social Network Analysis
SSC	Specialized Service and Supply Companies
STR	Stability of the ranking of the innovative firms
TV	Total Variety
USPTO	US Patent Office
UV	Unrelated Variety

1. Chapter 1: Introduction

1.1. Background

Resource based industries in general and the petroleum industry in particular are often understood as having limited capacity for growth and development. In addition to the well-known story of ‘resource curse’, they are also blamed for a capital intensive production function which restricts emergence of backward and forward linkages (Stevens, 2003; Nelson, 2008) and provides negligible developmental space. They are also classified as ‘mature’ sectors, exhausted of ‘technological opportunities’ for knowledge based economic growth. According to the standard measure of R&D intensity, oil and gas is usually classified as a ‘low tech’ sector. It appears near the bottom of the table of technology based classification, implying low innovation capacity (Acha 2002; R&D Scoreboard, 2009).

This study questions the adequacy of this line of reasoning due to its inadequate attention to the nature of the knowledge base underlying innovation processes. Exploring technological regimes of upstream petroleum industry as an example, this research provides an alternative or complementary argument. In contrast to the established picture, what appears to be restricted knowledge based growth and few cases of technological catch-up is not lack of ‘technological opportunities’, but ‘systemic complexity in the knowledge base’.

This is not to deny economic, political economic or institutional transmission issues such as price volatility, Dutch disease, social and political conflicts related to the control of resources[1]. These indeed may limit the advantages of recourse based industries for their associated countries, if they are not managed properly. Yet, the nature and characteristics of the knowledge base itself - such as complexity - can play an important role in preventing resource holding countries’ from the benefits of innovation opportunities. This important factor may operate even in the absence of other preventing factors recognized in standard ‘resource curse’ explanations. In other words, both sets of factors can potentially affect knowledge diffusion and

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[1] These mechanisms and transmission channels are addressed in more detail in section 1.2.

technological catch-up in latecomer countries. The present study analyses knowledge base complexity; while ‘resource curse’ theories and catch up literature both tend to focus on contextual and institutional factors, neglecting the importance of the nature of knowledge in learning processes.

Within the context of a Schumpeterian and evolutionary economic approach, this study sets ‘Sectoral Innovation Systems’ (SIS) (Malerba, 2005a & 2005b) as the broad analytical framework. It analyzes the relationship between knowledge base complexity as an important element of technological regime and catch-up in latecomer countries. The SIS framework was originally suggested to explain sectoral patterns of innovation. The main focus here is on the role of knowledge base complexity as an important but neglected aspect of technological regimes, though other dimensions may be touched upon when relevant. “The notion of technological regime provides a synthetic representation of some of the most important economic properties of technologies and of the characteristics of the learning processes that are involved in innovative activities” (Malerba and Orsenigo, 1997, p. 83).

One of the core messages of SIS literature is that technology related factors i.e. technological regimes play a key role in shaping sectoral patterns of innovations. It is shown that these patterns are systematically different across technologies and industries, but remarkably similar across countries (Malerba and Orsenigo, 1996; 1997). Technological regimes have often been defined as particular combinations of technological opportunities, appropriability, cumulativeness, and properties of knowledge base. The ‘properties of knowledge’ base which refers to characteristics of knowledge underlying innovative activities is itself a synthetic construct encompassing the degree of specificity, tacitness, ‘complexity’ and independence[2]. (Breschi et al., 2000, p. 391).

The original aim of the concept of technological regimes was to explain inter-sectoral variations in patterns of innovation (Breschi and Malerba, 2000; Malerba and Orsenigo, 1997). It could also explain variations in geographical patterns of innovation, based on the assumption that there is some correspondence between sectoral and geographical patterns of innovation (Breschi, 2000). The role of

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[2] These dimensions are defined in the chapter 3.

technological regimes in shaping international geographical pattern of innovation also recognizes similar arguments (Malerba and Montobbio 2003). The SIS framework has recently been extended to the analysis of technological catch-up processes highlighting the importance of sectoral differences in catch-up possibilities and strategies (Malerba and Nelson, 2010).

Nonetheless, systematic efforts to understand the role of knowledge base complexity in SIS studies in general, and in the context of latecomer countries in particular, are neglected. Only recently, catch-up theories began to pay attention to the role of technological regimens and the nature of knowledge in learning processes (Park and Lee, 2006; Kim and Lee, 2008). Even in these studies, technological complexity is overlooked, while the impacts of other characteristics of the knowledge have been relatively more researched. It is surprising that the role knowledge complexity has not been addressed in the catch-up literature, given the intuition that knowledge complexity could be a serious learning barrier for latecomers. In addition, lack of attention to underlying knowledge generation processes in resource based industries offers further attraction for academic research.

This thesis sits between the two gaps. On the one hand, knowledge base complexity in SIS literature is a relatively neglected area compared to other elements of technological regimes. On other hand, there is a lack of adequate understanding about the dynamics of the knowledge base in resource based industries. Upstream petroleum industry is considered relevant to both gaps. The analysis of the knowledge base of this sector could contribute to both literatures. On the one hand, it increases our understanding of the dynamics of knowledge base complexity in SIS literature. On the other hand, it feeds into the natural resource based development literature, providing a deeper picture of the opportunities and challenges involved in these sectors with regard to underlying knowledge and innovation processes.

Dominant approaches in the resource based development literature tend to provide an exogenous and static picture of natural resource industries, where the role of knowledge and innovation is relatively neglected (Andersen, 2012). These approaches are inadequate to explain the varieties of performance of resource based economies (Stevens and Dietsche, 2008). Also, they seem to have reached stalemate in providing fruitful policy implications, given the tendency to reject valuable opportunities involved in resource based industries (Bridge, 2008). Such weaknesses, along with recent changes in the global economy (Morris et al., 2011) have pushed researchers to question the assumptions of conventional wisdom and look for alternatives.

Alternative approaches are yet to provide a comprehensive theoretical framework and policy insights. However some common elements could be integrated under an emerging research program which could be ladled as a ‘knowledge’ (Lorentzen, 2008a) or ‘learning’ (Wright, 2001; Andersen, 2012) approach to resource based development. According to these new approaches, the performance and contribution of natural resource sectors to the economy is not something given, but a function of learning, innovation and knowledge accumulation in society. As a result, understanding knowledge generation and diffusion processes and the factors supporting or inhibiting them are on the top of this emerging research agenda.

The central aim of this thesis is to contribute in this promising research area through innovative analysis of the dynamics of the knowledge base of upstream petroleum industry and the associated sectoral, organizational and geographical patterns of innovation. The analytical focus is on *complexity* of the knowledge base, as an important but under researched area in the analysis of industrial and geographical dynamics. It is believed that a more systematic and dynamic conceptual and theoretical articulation of knowledge base complexity - what I call a dynamic three-dimensional perspective - and its application in the context of a resource industry, offers a number of important contributions. It increases our understanding of the nature of knowledge base development in the industry and revises the conventional view of the industry life cycle. In addition, its integration into available theoretical frameworks offers analytical value. In particular it helps explain the dynamics of modes of governance of knowledge (at sectoral and organizational level), international geographical patterns of innovation and catch-up processes.

This introductory chapter is organized in six sections. After the background described above, a brief review of dominant theoretical approaches to the challenges of resource based development and their analytical drawbacks are presented in section 1.2. Alternative approaches which broadly guided this thesis are reviewed in section 1.3 under the label of ‘learning’ or ‘knowledge’ view to natural resources. These are emerging partly as a response to the key challenges to conventional wisdom, and partly as a result of resurgence of natural resource industries on the global economy agenda. Section 1.4 explains the specific research questions this research aims to answer. Section 1.5 puts forward the research design employed to answer the research questions. The final section describes how this report is organized.

1.2. Motivation: challenges of resource based development and its theories

The literature on natural resource based development is dominated by the so called ‘resource curse’ thesis. Basically, it highlights the economic constraints of resource industries and theorises their possible harmful effects on industrialization, structural change and economic development (Auty, 2001; Gylfason, 2001; Sachs and Warner, 1995). According to this conventional view, specialization in natural resource industries is not a reliable option for economic development. Not only are natural resource industries themselves unable to provide a technological dynamism required for industrialization of the economy (or ‘technologization’ according Perez, 2008) and sustainable growth, they can also crowd out other sectors of the economy, decrease their competitiveness and shrink their size. Harmful effects could even go beyond economic sectors and hit the institutional set up of a country, distort the political processes, engender the formation of rentier states, and gradually lead to rentier societies characterised by a culture which stifles innovation and entrepreneurship.

This negative view of resource industries as relatively unattractive sectors has both historical roots and more recent extensions and developments. It dates back to the beginning of economics. Adam Smith warned against encouraging investments in mining projects which in his view “absorb both capital and stock” instead of replacing capital and generating profits from their stocks (Smith, 1776, 562). However this view became central to the development agenda in 1950, when structural economists attributed poor economic performance of African and Latin

American countries to their specialization in natural resources. At least three explanations have been suggested for this poor economic performance, each of them highlight different aspects of inherent nature of natural resource sectors.

First, Prebisch (1950) and Singer (1950) argued that weak economic performance of commodity exporters is due to the decline of Commodities-Manufactures terms of trade, or relative price of commodities compared to industrial manufactured products. This overall declining trend is linked to both demand and supply related factors. On the demand side, it is argued that commodities have a low elasticity of demand which prevents exporters from benefiting from demand expansion in commodity markets. Moreover, their growth rate is also slower than manufactures, because technological progress in manufacturing tends to be resource saving, substituting with synthetic materials. On the supply side, it is argued that natural resource industries are not technologically dynamic, because “they do not provide the growing points for increased technological knowledge, …and…direct Marshallian external economies” (Singer, 1959, p. 476). In addition, if they experience some limited technological progress, it mostly benefits consumers in foreign countries and not producing countries, because it translates to reduced prices not higher demand or profits. The combination of these factors contributes to the formation of long term decline in terms of trade.

The second challenge is the high price volatility on top of decline in terms of trade, which makes resource exporter economies very vulnerable. It harms resource based economies through abrupt changes in governments’ revenues, exchange rates, and local investment due to the high levels of uncertainty it creates (Nurske 1958). Some scholars argued that the damaging effects of these rapid fluctuations are even worse than the long term, but predictable, decline in the terms of trade (Cashin and McDermott, 2002).

The third argument refers to the weak capacity of natural resource industries for forward and backward linkages to the local economy. This is related to their capital intensive production function and their enclave geographical nature. It has been argued that their limited linkages to other sectors of the economy constrain learning, limit technological spill-overs and external economies, and provide little opportunities for job creation and skills development (Singer, 1950). Whatever beneficial impacts that potentially arise from these limited linkages, are also largely reaped in the home countries of large foreign companies. This transfer happens because of the special organization of their production process where foreign companies tend to import most of the inputs and capital equipment required in the production process, and export raw outputs for further processing in their home countries (Morris et al., 2011).

A more recent wave of these ideas was reinforced with a series of empirical econometric studies arguing for negative association between resource abundance and economic growth (Sachs and Warner, 1995, 2001; Auty, 1990, 1993; Gylfason et al, 1999). This range of explanations has extended more economic type explanations, like Dutch disease, towards more political-economy types, in which resource rents may distort decision making in institutions and political processes. The key difference of these explanations from previous ones is that they extend the scope of their analysis beyond what happens *within* natural resource sectors. The focus is on the damaging impacts of resource sector on wider environment and other sectors of the economy and society. For example, Dutch disease theory explains how the appreciation of the real exchange rate caused by expansion of commodity exports could lead to a contraction of tradeable sectors. This is because of the attraction of capital and labour away from manufacturing to the booming resource sector. In this view, the challenge is not just the resource sector itself, but its damaging impacts on the competitiveness of the other sectors of the economy which reduces its diversity and long term growth.

Although this conventional wisdom to resource based industries convincingly explains the *challenges* of natural resource based development, it has been *challenged based* on at least three different grounds. The *challenges* to conventional wisdom partly come from a misreading of the history of resource based development, partly from excessive generalizations and also partly from recent changes in the global economy. First, they misread the history, because the literature simply ignores the historical examples of successful resource based industrialization where these sectors are described as a blessing rather than a curse (Stevens, 2003). As a result it is unable to explain the variety of performance of resources based countries (Morris, et al., 2011).

Second, they tend to over generalize, because sometimes worst criticism of the worst forms of natural resource based industrial activity are generalized to other natural resource industries. However in many cases, they do not necessarily share the common characteristics (Marin et al., 2009). In its excessive form, the scope of generalization extends from sectors to countries and also over time. Finally, recent changes in global economy have raised new challenges for the application of conventional wisdom to the current area, even if they have been historically acceptable. For example, the historical downward trend of Commodities-Manufactures terms of trade has been recently reversed due to the increasing structural demand for commodities (Kaplinsky, 2006). In addition, it is argued that fracturing or segmentation of global value chain created new innovation opportunities (Morris, et al., 2011; Perez, 2008).

Lack of sufficient attention to these analytical challenges and unexamined assumptions in the ‘hard version’ of conventional wisdom has resulted in the widespread idea that natural resource industries are not a good platform for economic development. They are often described as low-tech, mature, undifferentiated sectors with low capacity for forward and backward linkage and innovation. The policy implication of this view is simply to ignore them in the development agenda and avoid as much as possible that economic development is based on these sectors.

Such an approach is clearly inconsistent with the experiences of several of today’s advanced countries such as USA, Canada, Australia and Norway which leveraged their natural resource sectors in the industrialization process (Wright and Czelusta, 2004). In addition, the policy lessons that can be drawn from this kind of analysis for many today’ natural resource based countries are very limited. It is not enough to understand how the natural resources might be a curse, but requires policies that could help countries avoid it or transform it to a sustainable blessing. Nonetheless, the perception of natural resources as a finite and exogenous good to the economic system which is subject to diminishing returns obscures the provision of more fruitful explanations and active policy suggestions. What seems missing is an evolutionary-institutional research approach with a dynamic perspective in which natural resource industries and their contribution to the economy are indigenized, as a function of a number of knowledge related factors and variables (Andersen, 2012a).

These are the promises of a revised version of conventional wisdom which combines lessons from resource curse with deep analysis of successful resource based industrialization that considers ongoing changes in the global economy. The premise is that "in order to understand the role of natural resources in economic development, they must be understood as dynamic, and as being subject to processes of natural resource creation, extension and obsolescing that are characterised by learning and capability building"(Andersen, 2012a, p. 291). Contributing to this emerging research agenda was one background driver of this PhD thesis. This research began with a broad motivation to provide a new understanding of the nature of resource based industries, and the opportunities and challenges involved in resource based economic development. The next section touches upon the main aspects of this emerging research agenda and locates this thesis in it.

1.3. Learning or Knowledge approach to resource based industries

This section argues how some important challenges to conventional wisdom in the analysis of resource based development could be resolved. Evolutionary economics and the Schumpeterian analysis of innovation provide valuable insights. They justify the application of the Sectoral Innovation Systems approach in natural resource industries, to avoid sectoral generalization and to take into account the role of technological and learning regimes in the dynamics and transformation of the industries. After a brief review of recent applications of the SIS approach in natural resource industries, its position in this thesis is described.

It is no surprise that a large share of revisions to conventional wisdom concerning the natural resource industries is drawn from the evolutionary perspective and the economics of innovation. Long term economic development in this framework is seen as the outcome of learning processes which involve co-evolution between technologies, organizations and institutions (Nelson, 1982; Kim and Nelson, 2000).

According to this view, learning and the accumulation of technological capabilities is the key to industrialization of the countries.

What is important for economic growth is the creation of *new* resources in the economy, not just allocation of *available* resources. This perspective is applicable to all kinds of circulating resources in the economy including natural resources. In other words, resources are not considered as something fixed and given, but contingent on the capabilities and capacities distributed in society and economy. As a result, there is nothing *inherently* wrong in natural resource industries. Consequently, they may play an important role in economic development, provided they induce learning and innovation. What make countries poor are not natural resources, but absence of learning and weak innovation systems (Andersen, 2012a & 2012b).

Therefore in the revisionist approaches to conventional wisdom, learning is the key defining variable for understanding the variety of performances among resource based countries. The analytical aim is to understand the learning processes attached to resource industries and the factors which may inhibit or stimulate them. It is also crucial to understand how learning happens in natural resource industries and how it affects innovation and structural change in the economy through co-evolutionary processes. This new orientation allows for the application of insights of evolutionary economics and the Schumpeterian approach to innovation in the analysis of resource based industries and their role in economic development. This capacity comes from the fact that deep understanding of learning and innovation processes has been sought for more than four decades. In particular, the innovation systems approach is highly relevant, because it takes into account the systemic and interactive nature of learning and innovation, and provides implications for innovation policy (Edquist, 1997 & 2001).

Among innovations systems approaches, the sectoral approach (Malerba, 2002; 2005) is specifically relevant to the analysis of natural resource industries because of features to be explained in more detail in chapter 3. It avoids sectoral generalizations and aims to explain how learning and innovation may differ among sectors. It also takes a dynamic and endogenous approach to learning and innovation. These features offer the capacity to address the challenges of conventional wisdom, as described above. Technological regimes and Schumpeterian patterns of innovation are introduced as key analytical concepts in this approach. In addition, technological regimes are considered as important factor in shaping geographical patterns of innovation and catch-up processes.

The need for a sector-specific, dynamic and endogenous approach to understand the role of natural resources in economic development has spurred a number of studies of natural resource based developments, both historical and more recent. Some of the more recent studies take an explicit SIS approach, while some older research implicitly applies some of its features. Here is a review of these kinds of studies which is meant to be illustrative rather than exhaustive.

In a historical study of the US mineral economy, David and Write (1997) show how the rapid expansion of mineral sectors led to the expansion of manufacturing creating increasing returns to scale and positive feedback mechanisms. A key driver for this resource led growth was the establishment of incentives, institutions and infrastructures which promoted learning in mineral sectors and the application of created capabilities in other sectors of the economy. A similar approach was extended to the successful development of mineral sectors in Australia and also South American and African countries (Wright and Czelusta, 2004). Again, the general lesson from these studies is the key role of learning processes in achieving the economic potential of natural resources, rather than to blame the inherent nature of natural resource industries.

Consistently, missed opportunities in Latin American countries compared to other successful endowed countries are attributed to lack of learning, not to the inherent unproductive nature of natural resource industries. Maloney (2007) argues that deficient learning and innovation capacity is responsible for missed opportunities, because of low investment in skills and technology infrastructure. Low incentives for learning and innovation were created by inward looking industrialization and protectionism.

In contrast, Finland and Sweden present more recent cases which reaped the economic opportunities of natural resource sectors such as timber and iron ore. Blomström and Kokko (2007) show how these Scandinavian countries upgraded the technological level of their raw material industries, combining natural resource intensity with knowledge intensity in innovative internationalized clusters. Nokia is presented as a tremendous success story of transition from natural resources to high-tech industry of electronics and telecommunications. All of these examples correct the one sided story of resource curse, showing the possibility of economic diversification alongside, not away from natural resources (Lorentzen, 2008a). What adds to the importance of natural resource based industries in the process of economic development is the fact that for some less developed countries, they are the only available source of comparative advantage, with no other viable starting point (Deaton 1999)

All the above studies suggest learning as a key process and knowledge as a key resource for successful natural resource based development, the idea first developed by innovation scholars (Lundvall and Johnson, 1994). Nonetheless, the sectoral innovation systems approach is only applied implicitly in these studies. The explicit application of innovation systems approaches in the context of natural resource industries in general and its sectoral approach in particular is very new. This field is emerging out of the combination of resource based development theories and insights from innovation systems approaches.

The increasing importance of natural resources in the global economy, rapid increase in their prices, and the social and environmental concerns attached to them, have speeded up expansion of this new field. New studies include both historical and current examples from both advanced and developing countries. They are not limited to academic research, but include a strong policy element with particular focus on natural resource rich regions such as Africa (Morris et al., 2011), South America (Perez, 2008; Marin, et al., 2009) and North America (Sharpe and Long, 2012). This seems to be a rapid race among regions to increase their fortune from this emerging opportunity.

Perhaps Lorentzen (2008b) is the first systematic attempt to apply innovation systems approaches in resource industries. The aim was to explore the drivers of learning, knowledge intensification and *lateral migration* of know-how and capabilities in the resource sector to other industries. The study covers comparative case studies of five resource industries in Africa and Latin America. Once again, as a response to the resource curse idea, the study confirms that resource based development is a possible, but difficult strategy. The authors call for further sectoral case studies, because in their view knowledge intensification differs from one sector to the other. Therefore, it is important to understand under what conditions knowledge intensification could be a successful strategy for industrial diversification.

Deep investigation of more cases should also clarify the effectiveness and efficiency of public policy in support of knowledge intensification process through better understanding of the knowledge base of resource industries. Another step forward was the publication of a collection of sectoral innovation systems in developing countries in which three out of ten cases were of natural resource industries (Malerba and Mani, 2009). They included pulp and paper in Brazil, Salmon farming in Chile and biofuels in Tanzania. The most recent case is the study of sugar cane in Brazil (Andersen, 2012b) which argued for the necessity of learning and building learning capabilities in order to enjoy the fruits of resource industries in less developed countries.

However, by definition, the sectoral innovation systems approach avoids sectoral generalizations. I chose to study the sectoral innovation system of upstream petroleum industry, as this sector is for many the main culprit and classic example of resource curse. There is a general agreement that many oil producing countries have not been able to follow knowledge intensification strategies to upgrade their technological capabilities and diversify their economies. On the other hand, there are other oil producing countries which actually did manage successfully to exploit their petroleum sector and diversify their economies.

Accordingly, the overarching question which informs the research in this thesis is:

Can the new ‘learning’ approaches to resource based industries provide a complementary explanation for the oil producing countries’ struggle to enjoy the innovation opportunities emerged in upstream petroleum industry, given the limitations of the conventional ‘resource curse’ view?

1.4. Research questions and the contributions

The aim of this research is different in scope and orientation from previous studies of sectoral innovation systems of petroleum industry (Acha, 2002, Sæthe et al., 2011; Engen, 2009; Dantas and Bell, 2009). Previous studies confirm that the petroleum industry offers technological dynamism. Norway (Sæthe et al., 2011; Engen, 2009) and Brazil (Dantas and Bell, 2009) are among a few oil producing countries which successfully combined oil production with technological innovation and related industrial diversification. While those studies analyze how Norway and Brazil caught up and developed their technological competencies in the petroleum sector, the main concern of this research is to understand why many other countries with oil production have made minimal contributions in technological innovation. What factors have prevented these countries to catch up in technological capabilities?

In order to answer this question, this study uses a broad coverage of sectoral innovation system both at global level and over time. It does not just focus on a specific country, although the innovative contribution of different countries is inevitably analyzed. The study takes a historical perspective over a relatively long-time period (1970-2005). This allows understanding the temporal context and path dependencies in industrial dynamics.

Basically, there are two ways to answer the overacting question. One is to focus on the context of individual countries and find the internal and structural factors which stifle learning processes - for example looking at poor policies or unsupportive institutions. The second way is to look at the characteristics of what needs to be learned or the *nature of knowledge*. Some kinds of knowledge can easily be obtained. Other kinds are difficult to learn. The aircraft industry is an example where it is difficult to learn knowledge. Although the aircraft industry has been a commercial industry for a long time, few countries have the technological capability for production and innovation in this sector. Obviously, these two ways to answer the question are complementary and do not exclude each other.

This study answers the overarching question by taking the second route. This is partly because I am more interested in finding an explanation for the scarce incidence or distribution of learning among oil producing countries, rather than focusing on a particular country. Also, the second type of analysis seems lacking in the literature. Only a few studies focused on the role of technological regimes or nature of knowledge in the shaping the geography of knowledge and catch-up processes (for example Park and Lee, 2006). The catch-up literature is largely dominated by the former type of analysis. It tends to focus mostly on the institutions or policies which may inhibit or stimulate learning. This orientation ignores the fact that the nature of knowledge and its characteristics in different industries may play an important role in increasing or decreasing the 'cognitive' barriers to entry and shape the organization and geography of knowledge.

My first intuitive idea came from my own personal experience in the industry. I also completed a review of the historical evidence about the upstream petroleum industry presented in the chapter 4. My guiding hypothesis was that the increasing technological complexity I observed in upstream petroleum industry matters in explaining low catch-up. In other words, my early hypothetical answer was that increasing technological complexity, not low innovation opportunities, has prevented latecomer countries from knowledge base development in upstream petroleum industry. This broad hypothesis turned to three main research questions which guided my systemic investigation of the patent data for the answers. My objective is to produce sensible answers to these three questions:

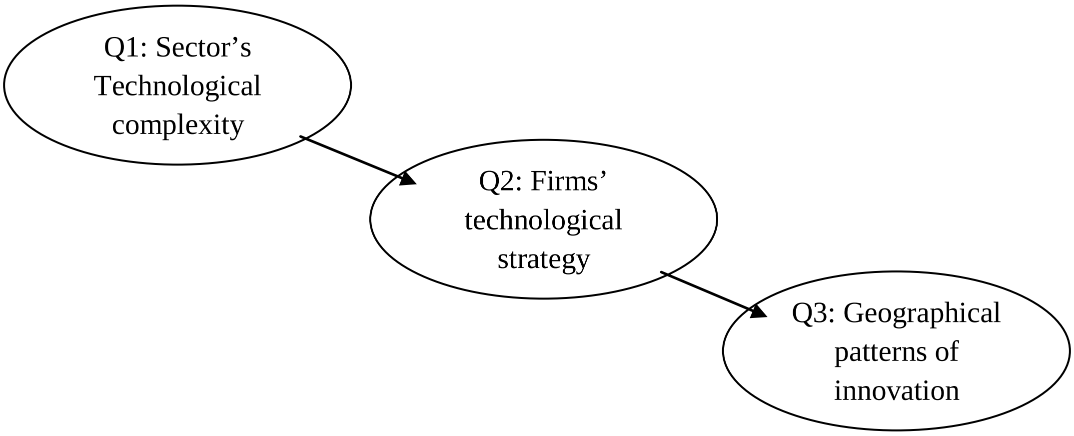
1- How has technological complexity in the upstream petroleum industry evolved over time?

2- How is the governance system of sectoral knowledge base adapted to the dynamics of technological complexity? And how have different firms responded or adjusted to the dynamics of technological complexity?

3- What are the implications of dynamics of technological complexity for the international geography of innovation and catch-up processes?

The first question explores whether patent data supports the idea that upstream petroleum industry has become technologically more complex. The second question investigates how firms' technological and innovative behaviour may change or be adjusted according to the dynamics of technological complexity. The third question explores how change in technological complexity affects the geography of knowledge and innovation at international level and shapes catch-up possibilities. The second question is a mediatory question, linking the first and third question through exploration of firms' technological behaviour. This is based on the belief that dynamics of complexity could only affect the geography of innovation and knowledge through firms' strategy towards knowledge and organization of innovation (fig 1.1). These are firms who decide how and where to perform their innovative activities. As a result, we are unable to understand deeply the impact of technological complexity on geography of innovation, unless we understand the impact of complexity on firms' or other agents' innovative behaviour.

Figure 1-1 Relationships between research questions



The three main empirical chapters of this research (5, 6, and 7) are organized according to these three research questions. In each chapter, the relevant literature is reviewed, appropriate hypotheses are proposed, appropriate quantitative methodologies are developed to examine the hypotheses, and the findings are presented.

This thesis offers three main contributions. At the theoretical level, it proposes a dynamic and three-dimensional perspective to knowledge base complexity. We argue that this view offers analytical values for explaining patterns of innovation at sectoral, organizational and geographical levels, while it also clarifies some of the conceptual ambiguities and theoretical inconsistencies about the impact of technological complexity in the literature. The second contribution is methodological where we develop a quantitative methodology to capture dynamics of knowledge base complexity and examine its association with patterns of innovation using patent data. Third contribution is empirical. The application of suggested methodology in a resource based sector is an empirical extension of studies of sectoral knowledge bases, as the third contribution.

1.5. Research design

This study is performed based on case study research strategy. This strategy is often suggested to answer ‘why’ and ‘how’ questions. It is suitable to study relatively contemporary events when the phenomena under study could not be the subject of experimental control (Yin, 2003). This strategy seems relevant to answer our research questions in this thesis which include both how and why type questions. The questions are about recent phenomena which because of its nature are out of experimental control. This case study has both descriptive and explanatory parts. In order to answer the first question, we attempt to describe the dynamics of technological complexity in upstream petroleum industry. In addition, the study also has explanatory elements. The dynamics of innovation opportunity and technological complexity has been explained with reference to historical and contextual factors such as oil prices and quantity and quality of technological demands. In addition, firms’ knowledge governance and innovation strategy, and their geographical implications are explained with reference to the dynamics of technological complexity.

The upstream petroleum industry could be seen both an *extreme* and as a *critical* case justifying this single case study (Yin, 2003). It is a critical case for the analysis of dynamics of technological complexity in resource base industries and its impacts, because the rising complexity in this sector is illustrative. It is an extreme case in the sense that it is a classical example and role model of many resource curse theories. For many, this industry is the main culprit in making resource based development unproductive or even counterproductive, as explained in the section 1.2. If the inadequacy of this line of reasoning is questioned with reference to this case, the way becomes open to ask this question for other cases.

The upstream petroleum industry could also be seen as an *extreme case* with the regard to the application of suggested data used and the methods employed. As will be explained in the next chapter, I analyse the dynamic of technological opportunities and complexities and using quantitative methods based on patent data. The main advantage of the patent data is that it is the only easily available database of technological innovations which systematically collects and classifies data for all industries with broad geographical coverage and over a long period of time. The long term nature of the phenomena under study and wide geographical dimension of the questions (patterns of catch-up among different countries) suggests that patent data are a very relevant and valuable data source for this study. However, patent data have their own drawback and limitations which are discussed in the next chapter. Petroleum industry could be seen as an extreme case for the suitability of data and methods used in this study. This is because patents are not the main method to protect innovation in this sector. If patent data and the proposed methodology are found relatively powerful in these minimal conditions, we are more confident to apply them for other sectors with higher knowledge and patent intensity.

I rely on *theoretical propositions* as the general analytical strategy for this case study, in which *pattern matching* and *time series analysis* are used as the main analytical techniques (Yin, 2003). In order to answer the main three research questions, I developed correspondent theoretical hypothesises relying on the background literature. In order to examine these hypothesises, I developed a set of measures and proxies to produce several time series and observe the dynamics of a set of variables over time. These variables are employed to capture the dynamics of knowledge base complexity, firms’ knowledge governance and innovation strategy, and international patterns of geographical innovation. Finally the observed empirical patterns are matched with theoretical prepositions and the questions are answered based on the degree of match or mismatch between theory and data. I also examined some of the available theories with respect to their analytical power in explaining observed patterns. This allowed moving one step towards *explanation building* (Yin, 2003). I suggest a conceptual extension of knowledge base complexity with a dynamic and three-dimensional perspective could increase the analytical power, if combined with some of the available theories.

This research runs at three levels of analysis and could be called an embodied case study (Yin, 2003). The dynamics of knowledge base complexity is analyzed at the level of the upstream petroleum industry where all the patent data is aggregated. The dynamics of governance of knowledge is analyzed at firm level. The analysis of geographical patterns of innovation is performed at countries' level. As explained in the previous section, these analytical levels are inter-related and their integration could increase the coherence and depth of this case study.

1.6. The structure of the thesis

The thesis began in this chapter by introducing my motivation for, and the significance of the topic, presenting the background literature, the research gap and the research questions. It explained how the overarching question of this study was developed from observation of the challenge of resource based development, and also the challenges of resource based development theories. Addressing these theoretical challenges, as explained, is the job of an emerging research strand which takes a 'learning' or 'knowledge' approach to resources based development. In order to contribute to this emerging area, three operational questions are developed with regard to the dynamic nature of knowledge base complexity and its role in sectoral, organizational and geographical patterns of innovation. A case study of the upstream petroleum industry is suggested as the suitable research design which will allow answers to the research questions from patent data.

In chapter 2, I articulate the research design including the research strategy, the rational for the choice of the upstream petroleum sector, the data sources used and the analytical strategy applied in this research. It is argued that the upstream petroleum industry is a critical as well as extreme case providing a suitable setting to answer the research questions and examine the suggested conceptual and methodological framework. The advantages and limitations of the patent data for innovation studies in general, and my databases for this research in particular are also addressed in chapter 2.

In chapter 3 I develop an analytical framework concerning the dynamics of technological regimes and associated patterns of innovation in sectoral innovation systems (SIS). It is shown that the sectoral innovation systems approach is inherently and conceptually defined as a dynamic framework analyzing the different drivers of changes and transformations in different industries. However, the mode of empirical analysis of the relationship between technological regimes and sectoral patterns of innovation, particularly in quantitative econometric studies, is dominated by static cross-sectional research designs. The provision of a dynamic reading of the concepts of technological regimes and sectoral patterns of innovation, and their relationship in this chapter paves the way for the empirical analysis of this dynamic framework in subsequent chapter. In addition, I introduce two other concepts of industry life cycle (ILC) and industry architecture (IA) in the chapter and discuss their relevance to SIS framework.

In chapter 4, I present data on the upstream petroleum industry from a sectoral system of innovation perspective. First, I briefly review the dynamics of the industry architecture as the background to understand the industrial dynamics and transformations of the sector. In this analysis which is mainly based on secondary data, it is shown how the vertical division of labour between different types of upstream companies (operators, integrated and specialized service companies) has evolved over time in response to the internal dynamics and external environment. This dynamic picture is completed by presentation of innovation trends, its drivers and its impact on the performance of the sector. The knowledge base of the sector and the configuration of major innovators in the sectoral innovation system of upstream petroleum industry are analyzed based on the original patent data base of this study.

Chapters 5, 6 and 7 are the results chapters where the relevant background literature to each research question is introduced and the correspondent hypothesises are developed. Also, the statistical methods for the examination of hypothesis and the proxies are introduced. Finally, the empirical results are presented and their implications for theory are discussed. Each chapter is allocated to one of the three research questions, respectively.

In chapter 5 and in response to the question of evolving knowledge complexity (Q1), a dynamic and three-dimensional perspective to knowledge base complexity is introduced. The ingredients of this view, which is in line with the dynamic reading of technological regimes presented in chapter 3, are drawn from the developments presented in the economics of knowledge. However the combination is a novel conceptualization of this study. In addition, three proxies are proposed in order to capture the three dimensions of dynamics of knowledge base complexity in upstream petroleum industry. The findings suggest that we could take a new ‘knowledge based’ approach to the industry life cycle model, where different phases are recognized according to the characteristics of the structure of the knowledge base, rather than ‘horizontal structure’ of the industry.

In chapter 6 and in response to the question of governance of knowledge base complexity (Q2), two complementary operational frames are developed which respectively capture the dynamics of sectoral and organizational patterns of innovation. The former which is based on the Schumpeterian patterns of innovation is more concerned of the relative role of the size (small vs. big) and experience (new vs. incumbent) of agents in the innovation process. The latter is more concerned of vertical division of knowledge between different types of players and their innovation strategy with regard to rate (growth vs. de-growth) and direction (specialization vs. diversification) of knowledge generation activities. Chapter 6 finally discusses how the shifts in both sectoral and organizational patterns of innovation of innovation are associated with the dynamic of knowledge base complexity.

In chapter 7 and in response to the question of geographical implications of the knowledge base complexity (Q3), an operational frame is suggested to capture the dynamics of geographical patterns of innovation. In addition, a methodology is developed in order to examine whether technological catch-up in general, and for which type of countries in particular could be observed in upstream petroleum industry. At the end of chapter 7, the association of dynamics of geographical patterns of innovation and catch-up processes with dynamics of knowledge base complexity is discussed.

Chapter 8 summarizes the findings, links them together and locates them in the wider academic discourse on the role of resources based industries in economic development. It also addresses the practical and policy implications of the findings for natural resource producing countries. Finally, it explains the limitations of this research and presents some suggestions for future studies extending different aspects of the current research.

2. Chapter 2: Research design

2.1. Introduction

The aim of this chapter is to introduce the research design and methodology. In chapter 1, I explained the background and motivation of the research followed by overarching and operational research questions of the study. This chapter explains how these questions will be answered addressing the overall research strategy and data collection and analysis methods.

The next section introduces the 'case study' approach as the relevant research strategy for this research with regard to the nature of research questions and phenomena under study. Section 2.3 explains why upstream petroleum industry was selected and what the implications of this choice are. In section 2.4, the data analysis methods are explained. In section 2.5, we introduce the nature of patent data in general, because patent data is the primary data source used to answer the research questions. We discuss briefly the advantages and limitations of patent data. Section 2.6 specifically speaks about the patent databases (Derwent and PATSTAT) used in this study. It describes the features of both databases and how they are combined to create a relevant dataset for this research. The concept of international patent family (IPF) is also introduced in the section 2.6, as the statistical strategy which selects more valuable patents and enables cross country comparisons. Finally, I explain how imperfections in the dataset are treated to produce reliable results. Section 2.7 summarises the chapter and concludes.

2.2. Case study as the research strategy

This study is performed using a case study research strategy. This strategy is often suggested to answer 'why' and 'how' questions with regard to relatively contemporary events when the phenomenon under study is not the subject of experimental control (Yin, 2003). More specifically, Yin (2003) distinguishes case study research as an empirical enquiry investigating:

- a contemporary phenomenon when
- the boundaries between phenomenon and context are not clear, and

- various data sources are used.

This strategy seems relevant to answer the research questions in this thesis which include both how- and why-type questions. The questions are about a recent phenomenon (dynamics of complexity and some of relevant impacts) which because of their nature are out of experimental control. In other words, it has happened in a natural, not experimental setting. As a result, we are not able to control neatly all the contextual variables influencing the phenomenon. However, multiple data sources (historical, qualitative, and quantitative) allow us to explore the important contextual factors and analyze their possible impacts over time.

This case study has both descriptive and explanatory parts. In order to answer the first research question, we attempt to describe the dynamics of technological complexity in upstream petroleum industry. In fact, this is our ‘how’ type question where the aim is to describe the evolution of technological complexity. In addition, the study also has explanatory elements. The dynamics of innovation opportunities and technological complexity are explained with reference to historical and contextual factors such as oil prices and quantity and quality of technological demands, or sectoral technical imperatives. In addition, we aim to explain firms' knowledge governance and innovation strategy, and the geographical patterns of innovation and catch-up processes, with reference to the dynamics of technological complexity.

In order to answer the research questions, a few research hypothesises are proposed according to the background information about industry evolution and theoretical and empirical literature. These hypothesises play the role of our first ‘guess’ about the reasonable answers to the research questions and guide our data collection and analysis stages.

While the primary data source for this study is patent information, a variety of secondary sources (such as scholarly publications, business and industry reports, companies’ websites, professional journals and the views of industry analysts are employed to get deeper insights). Patent data is the only rigorously classified information about technological innovation covering both long time periods and a wide range of countries, all of which are essential to answer my research questions. The combination of quantitative data and qualitative information in this study breaks the prejudiced view of the case study as an exclusively qualitative method. This study shows how quantitative methods can be used effectively in case studies, both to examine existing theory and as an input to build new theoretical accounts.

2.3. The choice of the case

The upstream petroleum industry can be seen as both an *extreme* as well as a *critical* case justifying this single case study (Yin, 2003). It is a critical case for the analysis of the dynamics of technological complexity in the resource base industries, because a glance at the drivers of change in the sector illustrates the transformation of the sector towards higher levels of complexity. However this study allows rigorous examination of this raw idea with empirical evidence. In addition, this industry exemplifies several phases of transformation and reconfiguration, providing a very relevant setting for the analysis of dynamics of technological regimes and patterns of innovation.

The dynamics of new discoveries and depletions alongside geopolitical change also create a highly dynamic geographical setting for this industry which provides a suitable test bed for the analysis of dynamics in the geography of innovation. The industry has been subject to technology policy interventions such as local content and technology transfer schemes in many countries in order to increase the local socio-economic benefits of upstream projects (Klueh et al., 2009). As a result, it is an interesting case to see the extent to which these measures resulted in the formation of innovation capabilities and catch-up in latecomer countries.

Upstream petroleum industry can be seen an *extreme case* in the sense that it is a classical example and role model of many resource curse theories. For many, this industry is the main culprit in making resource based development unproductive or even counterproductive, as explained in the chapter 1 section 1.2. If the inadequacy of this line of reasoning is questioned using this case, it is perhaps easier to question the adequacy of this line of reasoning in other resource base industries.

The upstream petroleum industry can also be seen as an *extreme case* with the regard to the application of suggested data used and the quantitative methods employed. As detailed in the next chapter, this study proposes to analyse the dynamics of technological opportunities and complexities using quantitative methods based on patent data. The petroleum industry can be seen as an extreme case because if patent data and the proposed methodology are found relatively powerful in these minimal conditions, we are more confident to apply them for other sectors with higher knowledge and patent intensity.

However, generalization from case studies is not expected to be 'statistical', but it is more of an 'analytical' type (Yin, 2003). Upstream petroleum industry is *not* a typical and replicable sample of other resource based industries to allow application of statistical generalization logic from sample to the population. Nevertheless, we expect to draw some 'analytical' general lessons from this study. That is, we expect under similar conditions, that the dynamics of technological complexity will express similar and consistent impacts in other industries. Nonetheless, this is subject to empirical investigation.

2.4. Data analysis methods

I rely on *theoretical propositions* as the general analytical strategy for this case study, in which *pattern matching* and *time series analysis* are used as the main analytical techniques (Yin, 2003). In order to answer the main three research questions, I developed correspondent theoretical hypothesises relying on the background literature (the hypotheses are presented in chapters 5, 6 and 7) and general insights about the historical evolution of the industry. These theoretical propositions play an important role in selection of relevant proxies, organizing the data collection processes and specifying relevant and non-relevant data.

In order to examine the proposed hypotheses, I developed a set of relevant measures and proxies which capture dynamics of a set of variables over time. Empirical measurement of these variables produces time series that allow the hypotheses to be examined. Observed empirical patterns are matched with predicted theoretical prepositions. The research questions are answered based on the degree of match or mismatch between suggested theoretical propositions and empirical observations.

The first set of variables refers to three dimensions of knowledge base complexity which answers the first research question. I discuss the proxies suggested for the breadth, depth and systemic complexity and illustrate their dynamics in chapter 5. We expect to observe the reflection of dynamics of knowledge base complexity in governance system of knowledge across the sector and firms' innovation strategy. This could answer the second research question. As a result, two other sets of variables are proposed to capture the dynamics of governance of knowledge under two different analytical frameworks in the chapter 6. One of these is based on Schumpeterian patterns of innovation analyzing the relative role of big vs. small and incumbent vs. new firms in the knowledge generation and innovation process. The other refers to the different firms' innovation strategy in terms of rate and direction of innovation (specialization vs. diversification). The expected association of dynamics of knowledge governance with the knowledge base complexity are examined based on the empirical observation of these measures.

We also expect to observe the reflection of dynamics of complexity in the evolution of geographical patterns of innovation and catch-up processes. This is because we expect firms to follow different geographical strategies when they face change in knowledge complexity. In order to examine this idea, to answer the third research question, another set of variables are proposed to capture the dynamics of geography of innovation in upstream petroleum industry. In addition an operational definition is presented to explore catch-up countries in the sector, using relative shifts in the countries share of innovation processes. This allows us to find out the catch-up countries, analyze their innovative behaviour over time and examine their association with dynamics of knowledge complexity.

After evaluation of suggested hypothesises, I also examined some of the available theories with respect to their analytical power in explaining observed empirical patterns. This allows us to move one step towards *explanation building* (Yin, 2003). I suggest a conceptual extension of knowledge base complexity with a dynamic and three-dimensional perspective could increase their analytical power, if combined with some of the available theories. These theoretical extensions are discussed in the final section of the results chapters of 5, 6 and 7.

This research runs at three levels of analysis which is usually called *embodied* case study (Yin, 2003). The dynamics of knowledge base complexity are analyzed at the level of the sector where all the patent data are aggregated. The dynamics of governance of knowledge is analyzed at firm level. The analysis of geographical patterns of innovation is performed at country level. As explained in the previous section, these analytical levels are related and their integration could increase the coherence and depth of this case study.

2.5. Patent data

Patent data are unique and rich information for studying innovation and technical change, although it has its own limitations. A patent is a legal document issued by governments for inventions characterised by a step of novelty and potential commercial application. This legal document grants a temporary monopoly right to the inventor to protect it and make profits on the commercial application of innovation in different markets. In turn, the inventor is obligated to publicly disclose the information of the invention for the benefits of the society. This information nowadays is often published on government's patent office websites. The requirements of the legal process for patent applications imply the formation of qualified patent databases with the detailed classified information on the nature of invention (its novels aspect, technical fields, industrial applications, etc.), and its assignee and inventors. As a result, patent data have for many years been an invaluable source of information for empirical studies of innovative activities and technical change since long time ago (see Schmookler, 1966, for one of the earliest studies). It is also accelerated recently by the availability of powerful computational technology.

The advantages and limitations of patent data for the analysis of innovative activities is a widely discussed issue in the literature (Pavitt, 1985; Basberg, 1987; Griliches, 1990; Archibugi and Planta; 1996; OECD, 2009). There are several advantages in patent data chief, for example:

- Because patents are the direct outcome of inventive process with expected commercial value, appropriate indicators could be drawn to capture the competitive and proprietary aspect of technological innovation.

- Because patent application process is costly and time-consuming, on average it is most likely to be sought for those inventions whose benefits are expected to be more than the costs. This feature filters out low quality inventions.

- Patent statistics are available for long time periods across sectors with wide geographical coverage which allows for effective cross-sectional and longitudinal studies.

- They are systematically categorised in very detailed hierarchical classification systems providing information about the direction of technical change, in addition to the rate of innovation.

However, it is particularly important to consider the limitations and disadvantages such as systematic biases in the data which may produce distorted results, if they are not treated properly. The main disadvantages are:

- Not all inventions are legally patentable. The classic example is software which is often protected by copyright. Moreover, the patenting scope may differ from one country to another depending on their particular patent law.

- Although some international agreements have become effective, in the end patents are binding within national territories. Because of different institutional structures in different countries which affect the length, time and effectiveness of protection, the inventor's interest may differ in terms of the countries where they seek protection.

- Patents are not the only or even the major tool to protect inventions. There are alternatives such as lead time and industrial secrecy.

- The patenting propensity is different among firms and industries. For some industries, a patent is a major competitive tool, while for some other industries it is not.

As a result, patents are only imperfect measures of innovation order. We should consider these limitations in our analysis. For example, countries with a basic level of technological capability can experience considerable progress in innovation which is not reflected in patent statistics. The type of knowledge produced at these capability levels, though very important, cannot lead to patentable innovations because of its imitative nature. In addition, patents are biased towards advanced manufacturing and therefore underestimate innovation services. Firms and countries that are specialized in service segments of a sector may seem less innovative in patent data, in spite of the knowledge intensive nature of innovation in services. Last but not least, patents could rise in some countries simply because of introduction of incentives, not because of technological innovations.

Although these limitations suggest that patents are imperfect proxies for innovative activities, we believe that results of this study are not seriously affected. This is because almost all of the conclusions in this study are drawn based on the analysis of the *trends* rather than actual *levels* of the suggested variables. Therefore, we expect imperfections to shift levels up or down without influential impact on the trends.

Patents are only a small part of the codified and patentable knowledge within each sector, often produced by highly advanced firms operating at the technological frontier. Therefore, patents might not convincingly capture many innovative and knowledge related aspects of industries which cannot be observed through patent data. Nonetheless, I have used patent data to draw conclusions in a relatively minimal and conservative manner. In my analysis of the knowledge base of the sector, patent data are only used to trace knowledge and the intensity of interaction between different technical fields. It is highly unlikely that the knowledge base of the sector has experienced a different pattern from that shown by patent data. A similar argument applies when industrial organization and governance of knowledge is considered, because follower firms often imitate innovation strategies (Barreau, 2002).

Regarding the catch up analysis, it is important to note that patents have not been used in this thesis as an indicator of technological catch-up for particular countries. It is clear that patent data can considerably underestimate technological progress in latecomer countries, as they are moving below the level of patentable innovation focused as they are mostly on imitative strategies. The geographical analysis suggested is based on *changing distribution of innovation* among different countries where the implications for catch-up countries are analytically drawn. With regard to the possibility of cross-country comparisons, I explain in the next section how the employment of patent families could reduce the margin of error and produce more reliable results.

2.6. The upstream petroleum industry patent dataset

Regarding the topic and the nature of this research, the data sources used should meet several conditions to allow the required analysis. First, it is preferred to provide a classification system which recognizes the upstream petroleum industry and its sub-sectors as a particular class and/or several sub-classes. This characteristic makes the process of finding related patents to the upstream petroleum industry easy, rapid and accurate. The keyword search strategy within patent titles, abstracts and claims is an alternative method which is more time- consuming, technically more complicated, and is not as accurate as a classification based method.

Second, the dataset should have sufficient global coverage to provide a worldwide picture of the technological base of the whole industry. Limited country coverage could bias the following analysis to the specific situation of selected countries which is not necessarily generalizable to other countries. More importantly, wide geographical coverage is necessary to analyze the dynamics of geographical patterns and catch-up in innovative activities.

Third, since catch-up processes usually happen in long time cycles, the data sources should cover long enough periods. Fourth, this research requires information about the countries of patent applicants and inventors for the analysis of catch-up processes. Fifth, the data source should also facilitate the recognition or building of patent families, either by providing pre-constructed family records or through the provision of priority information which is necessary for building patent families. Patent families are crucial for cross-country patent analysis to avoid multiple counting of the same invention when registered in different countries, to remove home advantage bias and to choose more valuable patents (Martínez, 2010b).

In my research, I could not get access to a single database meeting all these requirements. Therefore, a combination strategy was chosen to build a dataset from two different databases matched by patent publication numbers for each patent issuing authority. The Derwent Innovation Index and PATSTAT are the two databases employed in combination to provide all the information required for this research. A brief introduction to each database is introduced in section 2.6.1 followed by the combination procedure implemented in order to create the required dataset for this research in the section 2.6.2. Also, the choice of international patent family (IPF) as the basic unit of micro data is explained in section 2.6.3 as a statistical strategy to select more valuable patents and produce reliable cross-country comparison results. In addition, section 2.6.4 explains how imperfections in the data, such as missed country and company ownership structure, are treated.

2.6.1. Derwent Innovation Index and PATSTAT databases

To my knowledge, the Derwent Innovation Index[3] is the only patent database which provides a reliable patent classification for the upstream petroleum industry. It employs a clear definition and also recognizes different sub-sectors of the upstream value chain. This classification allocates the specific section of H to the petroleum industry in its Chemical Patent Index (CPI). It also subdivides patents to 9 sub-sections from H01 to H09, known as Derwent Class Codes (DCC), for different segments of the value chain from upstream to downstream and final products (Appendix I for the definitions).

In addition, each subsection is subdivided to groups in a hierarchical manner known as Derwent Manual Codes (DMC). The unique advantage of Derwent classification for this research is that the subsection H01 is allocated specifically to upstream petroleum industry. In addition, this section is subdivided into H01-A to H01-G sub-sections to differentiate between various segments of the upstream value chain (Appendix II for the definitions of the Derwent Manual Codes of the section H). There might be some patents which are assigned to several sections and classes at the same time because of the multi applicability and functionality of inventions.

The H01 Derwent class defined as “obtaining crude oil and natural gas - including exploration, drilling, well completion, production and treatment” clearly covers the upstream section of the value chain. Also, “general off-shore platform and drilling

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[3] I am very grateful of Thomson Reuters for providing free access to Derwent Innovation Index for the purpose of this research.

technology is included together with the treatment of tar sands and oil shales”[4]. The patent families registered in this class form the raw data for this study.

In addition to the Derwent classification system, this database also provides the 9-digit International Patent classification (IPC) codes attributed to patent documents. This allows recognition of the technical field(s) in which the inventions are performed. This classification is the source of diversification/specialization studies, as will be done in the chapter 6 in this research. While the IPC classification is mainly based on functions and technical fields of the inventions, the Derwent classification system is more based on the industrial application of the technologies.

The other advantage of the Derwent Innovation Index is that it provides patent information in family records which are constructed manually by experts. This feature again saves time and effort to build families from raw data, while offering higher accuracy when family building process is done manually by experts. I explain the advantages of using patent families in the section 2.6.3

The main drawback of Derwent database, however, is the lack of country coverage of patent applicants and patent inventors. This is a serious limitation for this research, given the strong geographical element in the research questions and the need to analyze catch-up processes. PATSTAT which is the EPO Worldwide Patent Statistical database is selected to compensate for this drawback. This database has been prepared specifically for the statistical analysis of innovative activities. It provides a wide range of information about patents including their applicants and inventor, and their original countries.

While Derwent covers patents issued in about 40 countries, PATSTAT provides patent information for more than 80 countries, doubling the geographical scope of patent publication authorities. The time coverage of both databases is more or less similar starting from the early 1960s up to 2009. The other difference is that PATSTAT provides simple DOCDOB and INPADOC extended families, while Derwent families are expert based manually constructed. The definitions and advantages of family-based

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[4] http://science.thomsonreuters.com/support/patents/dwpiref/reftools/classification/dclassh.html

data will be explained later in section 2.6.3. Table 2.1 compares both databases from the perspective of five criteria mentioned before.

2.6.2. The extraction and combination process

The number of records extracted from Derwent database in section H01 (upstream petroleum industry) was 115104 patent families for the data entered between 1965-2009 into the database. The Derwent entrance year which has some delays to the priority year (Wilson, 1987) has been the base for creation of the master set. The number of families is formed from 326357 patent publications (because every family could have multiple publications depending of the number of countries in which registered) of which 317445 were found in PATSTAT patent publication table. In other words, only 8912 patent publications were not found in PATSTAT either due to time mismatches between the two databases or errors in patent numbers.

Table 2-1 Comparison between two Derwent and PATSTAT databases

Criteria	Derwent Innovation Index	PATSTAT
1-Classfication for upstream petroleum	Yes	No
2-Global coverage	About 41 patent issuing authorities	More than 81 patent issuing authorities
3-Time coverage	Since early sixties up to 2009	Since early sixties up to 2009
4- Applicants and inventors information	Just names	Full information including country
5-Patent families	Manually constructed family based on priorities and technical content	Simple and extended family based on the priorities

Matching patent publications in the two databases was complicated and very time consuming, because patent publication numbers in the two databases follow different numbering format rules from one country to the other. Therefore, the first stage was to explore the publication number format for each country in both databases and then transform the Derwent publication number formats to PATSTAT publication number formats country by country. This process allows finding the equivalent records in the publication table of PATSTAT. The specification of publication number formats for each country in each database is provided by database producers. Extra complication comes from the fact that numbering formats have changed several times over time for some countries, and therefore the different transformation formulas are used for the same country during different time periods[5].

Table 2.2 illustrates the degree of match between the two databases by publication authority country (The total number of patent publications by each country on Derwent, the number of correspondent publications found and not found in PATSTAT, and the percentage of the patent publications of Derwent which are found in PATSTAT).

There are some countries such as India, Czechoslovakia, Philippines, Korea, Mexico and Hungary where their patent publications present low match percentages. This mismatch should not be problematic as long as the other members of the same family of these publications are found in the database, because members of the same family are common in other information such as inventors and applicants of the patent. Given the selection of international patent families which are published in several countries (will be explained in the next section) for cross-country comparisons, I am confident that the results are not affected by this mismatch. This is because; it is very unlikely that all the publication information of international patent families in different countries is missing. For example if the publication information of an international patent family in India is missing, the publication information of the same family in other countries is very likely to complete the dataset.

Mapping the publications records obtained from PATSTAT into Derwent patent families could clarify how many patent families with matched information we have. This process shows at least one publication in PATSTAT is assigned to 113454 Derwent families out of total 115104 families. In other words, in only 1650 families out of 115104 (less than 1.5 percent) has the matching process been unsuccessful. Hence, all the subsequent analysis is based on these matched records.

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[5] The transformation algorithm used for this matching process is available on request

Table 2-2 The degree of match between Derwent and PATSTAT records

Country Code	Country	No. Found	Total No.	No. Not found	Match %
AR	ARGENTINA	11	11	0	100.0
AT	AUSTRIA	291	291	0	100.0
AU	AUSTRALIA	15164	15909	745	95.3
BE	BELGIUM	590	590	0	100.0
BR	BRAZIL	5881	5917	36	99.4
CA	CANADA	26033	26060	27	99.9
CH	SWITZERLAND	173	174	1	99.4
CN	CHINA	14755	14832	77	99.5
CS	CZECHOSLOVAKIA	37	202	165	**18.3**
CZ	CZECH REPUBLIC	91	122	31	74.6
DD	GERMAN DEMOCRATIC REPUBLIC	664	674	10	98.5
DE	FEDERAL REPUBLIC GERMANY	15121	15179	58	99.6
DK	DENMARK	1300	1314	14	98.9
EP	European Patent Office	30706	30787	81	99.7
ES	SPAIN	1359	1402	43	96.9
FI	FINLAND	764	773	9	98.8
FR	FRANCE	8674	8674	0	100.0
GB	UK	26171	26208	37	99.9
HU	HUNGARY	309	468	159	**66.0**
IE	IRELAND	58	81	23	71.6
IL	ISRAEL	205	209	4	98.1
IN	INDIA	0	1267	1267	**0.0**
IT	ITALY	1133	1250	117	90.6
JP	JAPAN	9425	9518	93	99.0
KR	KOREA	418	1320	902	**31.7**
LU	LUXEMBURG	7	7	0	100.0
MX	MEXICO	2171	4644	2473	**46.7**
NL	NETHERLANDS	2974	2979	5	99.8
NO	NORWAY	19056	19308	252	98.7
NZ	NEW ZEALAND	381	394	13	96.7
PH	PHILIPPINES	20	95	75	**21.1**
PT	PORTUGAL	139	169	30	82.2
RO	ROMANIA	976	1030	54	94.8
RU	RUSSIA	12191	12330	139	98.9
SE	SWEDEN	1063	1164	101	91.3
SG	SINGAPORE	390	430	40	90.7
SK	SLOVAK REPUBLIC	61	61	0	100.0
SU	SOVIET UNION	21670	22631	961	95.8
TW	TAIWAN	174	316	142	**55.1**
US	US	70032	70463	431	99.4
WO	WO	25345	25360	15	99.9
ZA	SOUTH AFRICA	1462	1510	48	96.8
	Total	317445	326357	8912	**97.3**

2.6.3. Derwent International Patent Families

“A patent family is a set of either patent applications or publications taken in multiple countries to protect a single invention by a common inventor(s) and then patented in more than one country. A first application is made in one country – the priority – and is then extended to other offices"[6] (EPO, 2012). Although the definition seems straight forward, it is operationalised in different ways, because patent documents often have several priority countries which are entered into database in different times (Martinez, 2010a).

Given the availability of Derwent families in my database which defines families based on the similarity of their technical content, my analysis in this research is based on Derwent families[7]. One advantage of Derwent family is the control of the quality of created families by experts, reducing the margin of error compared to automated computer based algorithms (Martinez, 2010a). In PATSTAT, two other types of simple DOCDOB and INPADOC extended families are introduced which are created based on priority information and by an automated process[8]. Because Derwent families go through the quality control process by experts and also provide a more relevant definition in terms of similarity of *technical content* of family members, they are selected as basic information records of this study.

In general, several advantages have been mentioned for using patent families instead of single patent information in statistical analysis of innovative activities. To avoid double counting, to remove home advantage bias, to provide a more reliable base for cross-country comparisons and to estimate patent values are among the most important advantages (Martínez, 2010b) which are relevant to different parts of this study.

There are several options to filter out the families that we do not intend to include in the analysis. Some authors believe that it is better to build patent indicators using single patent office patent families, because different legal and administrative procedures in different patent offices distort the data and make the comparison difficult (OECD, 2009 p.60). This means that, in the analysis of the technological underpinning of the upstream petroleum industry, we rely only on the patents issued by just one patent authority. However, reliance on single office patents has its own weaknesses. In addition to home

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[6] http://www.epo.org/searching/essentials/patent-families.html

[7] For the details of the definition see: http://www.epo.org/searching/essentials/patent-families/thomson.html

[8] For the details of the definition see: http://www.epo.org/searching/essentials/patent-families/definitions.html

advantages bias (over representation of local companies compared to foreign companies), patents issued by each country usually reflect the market conditions for those technologies which are attractive for that country. Therefore two kinds of errors might occur, if the aim is to analyze the inventions at the global industry level. First, we do not know how attractive and therefore generally applicable those technologies are in other markets. Second, the analysis would not include those technologies which are created and applied for in other countries but did not seek protection in the selected target country.

To reduce these kinds of errors when there is no a ‘unified global patents systems’, one suggestion is to focus on a ‘representative’ country which is usually supposed to be US patent office (USPTO)[9]. It is argued that claims submitted in other countries, are often also applied for in USPTO at the same time for international recognition and seeking protection in the largest and most advanced market (Schwartz, 2003; Huang et al., 2003). The extent to which this hypothesis is valid for the upstream petroleum industry is not clear, particularly because part of technologies used in this industry are location specific and compatible with specific geological conditions of particular markets. In spite of this weakness, patents registered in the US patent office are still popular in cross-country comparisons (e.g. Park, and Lee, 2006; Jang, et al., 2009). This is because attractiveness of the US market is a strong incentive for many companies to protect their inventions either as the first option or as the second designation following their home country.

Nonetheless, the application of single member families which are issued in a single patent office has another weakness, in addition to the home bias problem which mentioned before. This problem seems applicable to all analysis based on single member families including US families. It treats both less valuable domestic families (which their protection has been sought just in one country and may have negligible economic value) and more valuable non-domestic families (which their protection has been sought in several countries and may have higher economic value) equally. In other words, there might be some country specific mechanisms at work promoting low quality patenting behaviour where for example the cost of national patenting is very low and

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[9] US patent office

covered by governments. In these kinds of cases the possibility of low quality patents which are never converted to innovation is high. In opposite, if protection for a patent is sought in other countries which usually involve high costs, it is safe to expect higher returns to that invention.

To address this weakness, several restrictive criteria have been suggested to exclude less valuable families and focus the analysis on the more valuable families providing a more reliable base for international comparisons.

Three types of suggested restrictions are non-domestic, transnational, and triadic families with the following definitions (Martinez, 2010a, p. 20):

1. 'Non-domestic' families are those which have at least two members from different patent offices and therefore exclude pure domestic families with one member from just one single country.
2. 'Transnational' families are those including at least one PCT (Paris Convention Treaty) or one EPO application
3. 'Triadic' families, are defined as those which have at least one USPTO, one EPO and one JPO (Japan Patent Office) patent application as family members

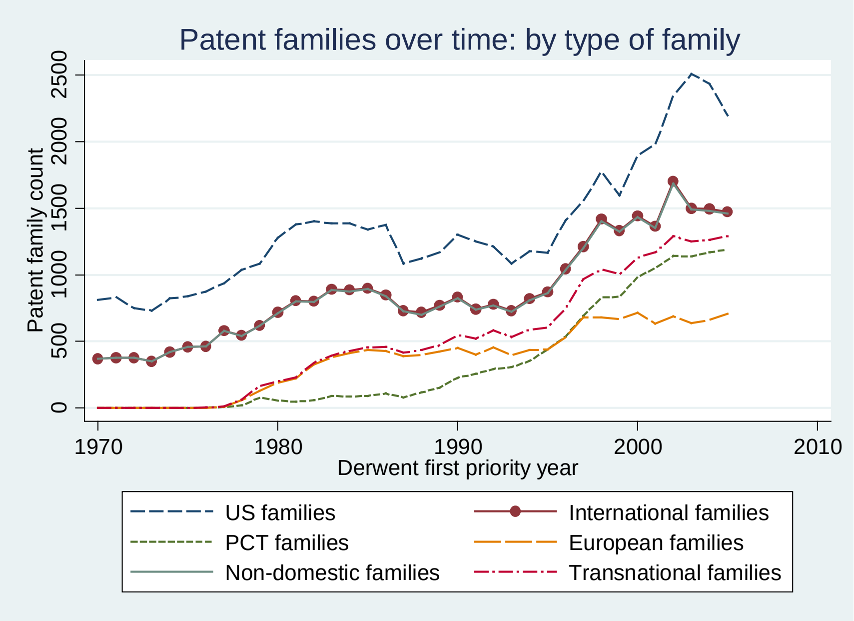
As it is clear from the definitions, the first one is less restrictive, the last one is too restrictive and transnational families take a middle position in terms of inclusiveness. To decide which definition of patent family fits better with the aims of this study, we should consider the advantages and limitations of each filter and the degree to which they could provide a more reliable, but at the same time inclusive analysis for the upstream petroleum industry. I exclude the third definition, because it is too restrictive. It is not very relevant to the operation of upstream petroleum industry, because Japan is not perhaps a very important market of upstream related technologies.

The patterns of the transnational families alongside of its two constituents (PCT and EPO families) and also US and non-domestic families in upstream petroleum industry are illustrated for comparative purposes in figure 2.1. As mentioned before, transnational families could solve the problem of home advantage bias to some extent, because all countries have the foreign status in these offices. Despite this advantage in transnational concept, comparison with US or non-domestic families in figure 2.1

suggests that the long history of technological activities in the upstream petroleum industry before 1990 will be lost, if we concentrate only on transnational families. This is because these international patenting regimes were set up relatively late.

Also, in spite of considerable data availability during 90s, the transition period to these international routes of invention protection which continued until 2000 does not allow for reliable international comparisons before this time (Frietsch and Schmoch, 2010). In other words, the late beginning of the working of both international routes offices around 1978 and different long delays in adoption of theses international routes for patenting by different countries make meaningful comparisons difficult, particularly before 2000. As a result, differences between countries might be due to different adoption times rather than real innovativeness.

Figure 2-1 Trends of different types of patent families in upstream petroleum industry



On the other hand, non-domestic families and US families illustrate an overall similar pattern, covering inventions from the early 1970s. This suggests that before establishment of PCT or European routes, the US patent office was mainly playing their role as the ticket to international protection. Regarding this situation, reliance on non domestic families may not be as unbiased as the transnational families for cross country comparisons particularly in the case of US patents, but this is the only available source, if the analysis should cover the period before 90s.

Within the framework of this limitation, I suggest using the combination of ‘non domestic’ and ‘transnational concepts’ to be able to take advantage of both in this study. It means while we reduce home country bias (which is dominant in US families), we also have the advantage of long coverage of the data since 1965. I define this combination as ‘international patent families’ (IPFs) created by the aggregation of non-domestic and transnational families. The trend of international patent families overlays non-domestic trend, as by definition, transnational patents should be a part of non-domestic families. Nonetheless, in theory they might be a bit different, since the transnational families which have not still reached to national level are not included in operational definition of non-domestic families. This is because they should be registered at least in two countries.

In sum, all the data and analysis presented in this study is based on IPFs drawn from the Derwent families database, unless stated differently. This combination partly compensates for home advantage bias, selection of more valuable patents, but at the same do not lose pre-1990s records of inventions when no international routes had been established for patenting. The trend of this data is shown as the dotted line in the figure 2.1.

2.6.4. Dataset imperfections

There are two types of imperfections in our dataset which need special treatment. The first imperfection is the registration of firms’ inventive activities under different names in the dataset. This may create problems for our firm level analysis. This happens largely because different affiliates of the same company, particularly their branches in different countries may apply for patents independently using their official local names. The result is the attribution of the inventive activities to different company names which are in fact different affiliates of the same entity. The second problem is the large size of missing data (about 50%) in the PATSTAT inventors’ country. This large share of missing country data could distort our geographical analysis, if is not treated properly. I managed to overcome both imperfections with acceptable precision levels as explained below.

The Derwent database has partly solved the first problem by attribution of a 4-letter assignee code to major patentees with more than 1000 patents. They get the same assignee code if they are owned by the same entity, even if they patent under different names (Derwent, 2011). Using these 4-letter assignee codes could aggregate the inventive activities of big companies linking different affiliates to the same entity. Part of the problem however remains, because of the smaller patentees which do not have standardized codes. Their invective activities may be underestimated in the analysis, as their patents may be dispersed under different names. A process of manual matching for the entities with more than 30 patents was performed in order to reduce this problem. In other words, I searched for different names of the companies with more than 30 patent and grouped different affiliates together with a manually created code. This complementary procedure is expected to have reduced the margin of error to a large extent. Nonetheless, given the reliance of my analysis on trends rather than absolute levels, the remaining imperfections should not affect the results.

In order to solve the second problem and reduce the number of missing countries in my dataset, I implemented a relatively complicated procedure which is explained in appendix III. Three sources (of priority country, assignee country and main inventions country of patent assignees) are used in combination to estimate the inventor' country with minimum margin of error. After the application of this procedure, only about 10% of the patent families remained with missing inventors' country. We assume this 10% could not seriously change the results if is randomly distributed among countries.

2.7. Conclusion

In this chapter, I addressed different aspects of the research design through which the research questions are to be answered. I argued that a case study approach is the appropriate research strategy for this research, because it is focused on the contemporary phenomenon of dynamics of knowledge bases complexity in a natural setting. In addition, the nature of research questions which are of a 'why' and 'how' type suggests the case study as a suitable method.

With regard to the choice of the single case of upstream petroleum industry as the empirical setting of the study, I argued that this sector can exemplify both a critical and extreme case. It is a critical case for the analysis of dynamics of complexity and its impacts, because the sector has experienced some dynamics towards technological complexity. The industrial dynamics and transformations of the sector, in terms of structure and geography, provide a rich setting for study of industry evolution and the role of complexity in these transformations and reconfigurations. The sector can also be seen as an extreme case in two senses. First, it is often seen an extreme case and main culprit for resource curse, relative to other resource based industries. It is also an extreme case in terms of the quantitative methods applied based on the patent data. As a result, it can facilitate the replication of similar studies both in terms of the topic and method in other natural-resource industries.

The broad analytical strategy for this research is pattern matching whereby the theoretical predicted prepositions are examined against empirical observations. Patent information is suggested as the primary source for this research providing rich information about the rate and direction of innovation and knowledge generation in the sector. The legal requirements of the patent authorities imply relatively high quality of the wide range of the data. This includes detailed classification of inventions as well as the location of inventors and applicants for a relatively long time period. While these advantages offer a good opportunity to answer the research questions, we need to be careful about some caveats in the patent data. The concept of international patent families is introduced to reduce two main challenges of patent data. This filter not only selects the more valuable patents which are important in analyzing innovation capabilities, it also reduces the home advantage bias that involved in studies based on families from single patent offices.

Finally, it is explained how the dataset of international patent families in upstream petroleum industry created, tidied up and its imperfections are amended to provide a more reliable source of the data for this research. I explained that the Derwent database is chosen first, because it has a classification system which particularly recognises the upstream petroleum industry as a specific sub-section (H01) and also provides its records in qualified Derwent family format. The information of inventors' and applicants' country which are not available in Derwent database is drawn from PATSTAT database which are matched and combined according to publication numbers. The amendment of missing country data through the combination of other sources and grouping of the companies with different names and affiliates in the dataset were the final stages. They reduce the imperfections in the dataset creating a reliable raw data for the analysis performed in this thesis.

3. Chapter 3: Sectoral Innovation Systems approach and dynamics of knowledge base complexity

3.1. Introduction

This chapter introduces the sectoral innovations systems (SIS) approach as the broad analytical framework for this research. It explains the advantages of the framework in general and its relevance to the study of innovation in upstream petroleum industry in particular. It explains the building blocks of the SIS framework and also the main theoretical concepts employed in sectoral studies. As such, the role of technological regimes in sectoral and geographical patterns of innovation is discussed. Two important features make SIS a relevant framework for this study. First is its attention to the role of knowledge base complexity as one of the important dimensions of technological regimes. Second is its dynamic perceptive on the nature of sectors.

The central argument is that sectoral innovation systems should be analyzed in a dynamic perspective. In this framework, shifts in technological regimes over time could change the dominant sectoral and geographical patterns of innovation. While this dynamic relationship is conceptually acknowledged in the literature (Malerba, 2002, 2005a), empirical analysis of this connection is dominated by a static cross-sectional mode of analysis (Malerba and Orsenigo, 1996; 1997). Likewise, the knowledge base complexity has been introduced as one of the dimensions of technological regimes. However, it has been relatively neglected in empirical studies of sectoral systems. This study extends the SIS literature in both respects by empirical examination of the role of knowledge base complexity incorporated within a dynamic analytical framework.

Recent evidence has clearly documented that the creation and development of 'high-technologies' are no longer the exclusive business of 'high-tech' industries (Robertson and Patel, 2007). Over the last two decades, 'low-tech' industries have become major contributors to the development of 'high-tech' knowledge side by side with advanced new industries. This contribution has not been just by creating a large and passive demand, stimulating adoption and diffusion of new technologies created in other industries. In fact, global corporations in traditional business areas have been actively involved in development and introduction of new technologies. This role is visible even in paradigm changing technological domains such as ICT, biotechnology and new materials. Therefore, recent research[10] on innovation in traditional industries considers the low-tech high-tech distinction among industries as sometimes misleading. This classification implicitly underscores the innovative power of ‘old economy’ sectors (Robertson et al., 2009; Robertson and Patel, 2007; Mendonça, 2009).

Likewise, the traditional distinction between ‘mature’ and ‘emerging’ industries has been put into question, based on new evidence on innovativeness of old and traditional sectors (Acha and Brusoni; 2005). This distinction is largely based on conventional industry life cycle model (Abernathy and Utterback, 1978) which tends to conceptualize industries as “mortal corpus” (Acha and Brusoni; 2005). This approach assumes technological opportunities are being exhausted over time.

However, there is considerable evidence that this model was proposed based on industries of the first half of the twentieth century. This is not necessarily valid for the dynamics of many of today’s industries either in traditional sectors such as tyres (Acha and Brusoni; 2005; Brusoni and Sgalari 2006) or in modern sectors such as telecommunication and biotechnology[11] (Grebel et. al., 2006). Although they develop over phases of change and transformation, it does not necessarily mean they lose their innovation and knowledge intensity over time. In contrast, there is pervasive evidence that mature industries are no less innovative than new industries (McGahan and Silverman, 2001). They can reinvent themselves from within and regain their innovation and growth capacities, after many years (Klepper, 1997).

Given these broad trends, we need a dynamic analytical framework which puts learning and innovation at the centre of analysis. First, it should take into account the technological complexities of the current status of industries. The innovative capacity and technological complexity of so-called mature and traditional industries such as the upstream petroleum sector are sometimes overlooked. Indeed, we may need to revise

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[10] For wider literature look at special issue of Research Policy Volume 38, Issue 3 on ‘Innovation in low and medium-technology industries’ (Robertson et al., 2009)

[11] In fact, it might not be accurate to look at some these modern sectors, as ‘industries’, because they are a bundle of general purpose technologies with pervasive applications in other sectors

our old classification devices in the light of new phenomenon. Second, we should take into account different systemic factors that shape and influence leaning and innovation processes creating industrial dynamics. Third, we need to take a flexible and dynamic approach to the definition of sectoral boundaries, given the increasing and changing interdependencies among different industries.

The concept of Sectoral Innovation Systems (SIS) was put forward to provide a multidimensional, integrated and dynamic analytical framework in line with these requirements. The SIS approach is a broad and flexible tool to study the dynamics and transformation of the sectors. Nonetheless, it does not assume a uniform pattern of development over which all industries are supposed to proceed. In contrast, it emphasises the differences among industries shaped by different technological and learning regimes. In particular, its focus on the role of knowledge and learning processes in transformation of the sectors and its flexibility for the definition of sectoral boundaries is very relevant. On top of these methodological features, knowledge base complexity - which is the focus of this research - is considered within SIS framework as one of the elements of technological regimes. This chapter aims to introduce the SIS approach and some related concepts. The central emphasis is on dynamic perspective to knowledge base complexity as an important factor in shifting Schumpeterian patterns of innovation and SIS transformations.

This chapter is organized as follows. The next section introduces the SIS approach and its theoretical roots, features and main building blocks. A related sectoral classification of the patterns of innovation based on Schumpeter is presented in a dynamic perceptive in the section 3.3. The notion of technological regimes is the subject of section 3.4, as a core explanatory concept in SIS framework which shapes the Schumpeterian patterns of innovation. The dynamics of knowledge base complexity is explored in the section 3.5 as an under researched area in SIS approach. Section 3.6 discusses the links between technological regimes and geographical patterns of innovation. Section 3.7 summarises the analytical framework and key concepts discussed in the chapter as a template which integrated subsequent empirical and theoretical chapters.

3.2. Sectoral innovation systems (SIS)

This part introduces the Sectoral Innovation Systems (SIS) approach and explains its main theoretical contributions. It also briefly introduces Industry Life Cycle (ILC) and Industry Architecture (IA) as two related but different concepts to SIS, which are used in this research.

“A sectoral system of innovation and production is a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products” (Malerba, 2002, p.248)

The concept of SIS draws from the traditions of evolutionary economics and systemic approaches to innovation. Attention to knowledge and learning processes, central focus on competencies and the dynamic approach come from the evolutionary camp. In this dynamic approach, SIS also has broad relevance to the industry life cycle literature (Utterback, 1994; Klepper, 1996) as well as the research stream on long-term evolution of industries, as could be found in the writings of Schumpeter, Kuznetz and Clark (Malerba, 2002).

It borrows its systemic approach from innovation system literature (Edquist, 1997), which focuses on actors, their relationship and interactions, and their institutional environment in which they operate. This concept is best understood as complementary to other similar concepts. National innovation systems focuses on national boundaries (Freeman, 1987; Nelson, 1993; Lundvall, 1993) and regional/local innovation systems takes a regional boundary (Cooke et al., 1997). Technological systems focus on networks of agents involved in the generation, diffusion and utilization of particular technologies (Carlsson and Stankiewitz, 1995; Hughes, 1984; Callon, 1992). Although they vary in terms of analytical boundary, they consider the systemic nature of innovation processes.

While SIS has many commonalities with these concepts in terms of its core analytical approach, it departs from all of them in its delimitation boundary at sectoral level. Accordingly, the central question that this approach tries to answer is “How and why innovation differs across sectors?” (Malerba, 2005a, p.14). In this view, sectors are often defined based on related or substitutable product groups which serve a given or emerging demand with an underlying common sector specific knowledge. Building on these intellectual traditions, SIS provides a multidimensional, integrated and dynamic view of sectors in order to understand and explain structure and organization of innovative activities (Malerba, 2002).

This approach often proposes three main building blocks to define and analyse sectoral systems: (for more information: Breschi. and Malerba 2000; Malerba, 2002, 2004, 2005a & b)

- Knowledge and technological domain
- Actors and networks
- Institutions

The role of demand and user-producer interactions in the innovation process is also considered important in the innovation process.

Knowledge and technological domain:

The specific knowledge base, technologies and inputs are important elements of a sector. In fact, they can set the boundaries for the sector in a dynamic perspective. Accordingly, as the knowledge base and working technologies of a sector change, its boundaries also change over time. In addition, complementariness and technological interdependencies are also important in defining relationships between sectors. The particular focus of SIS approach on the role of knowledge base and its characteristics in shaping the structure and organization of innovative activities is its attractive and relevant feature for this research. I will elaborate more about the knowledge base in the next chapter.

Actors and networks:

A sector is composed of heterogeneous actors of both firm and non-firm organizations (individuals, universities, research organizations, etc.). They are involved in the generation and introduction of innovations and production of goods and services. In the SIS approach, they are characterized by specific sets of beliefs, objectives, expectations, capabilities and learning processes. They may have different types of interactions and relationships with each other from communications, knowledge exchange, and cooperation, to competition or command. These relationships form the networks in which actors may have both market and non-market interactions.

The types of networks and the structure of relationships may differ among sectors. They are shaped by knowledge base characteristics, learning processes, underlying technologies and their complementarities and interdependencies. The structure and pattern of innovative activities may change over time in the same sector, as a consequence of changes in the knowledge bases and relevant learning processes. In other words, the role of different actors and their relative position in the innovation network may change when new divisions of labour emerge.

Institutions:

Institutions are defined as norms, rules, laws, common habits and practices which shape actors' cognition, actions, interactions and behaviour. They include both formal types such as rules which are legally binding or informal types which are established and accepted through practices.

In addition to the three above mentioned building blocks, *demand* is often considered as a key part of the system. It is shaped by different types of users, their goals and learning processes, and their interaction with other types of agents. User-producer interactions are considered very important in the innovation process. Transformation of the nature of demand could play a very important role in the dynamics and evolution of systems, as will be seen in the case of upstream petroleum industry in the next chapter.

SIS is a dynamic system which may change and transform over time in response to several processes. According to the evolutionary view (Nelson, 1995; Metcalfe, 1998), two very general processes of variety creation and variety selection could be identified. This variety creation and selection could refer to products, technologies, firms, institutions as well as actors' strategies and behaviours with regard to R&D and innovation. More specifically, a sectoral system may experience evolution and transformation due to co-evolution of its various elements. For example, particular interactions between technology, industrial structure, institutions and demand are addressed in the literature (Nelson, 1995; Metcalfe, 1998). In this dynamic view, transformation of existing sectoral systems as well as emergence of new ones is at the centre of analysis.

For example, integration and creation of interdependencies between previously separated knowledge and technologies could change the configuration of the system and relationship between actors. It may lead to creation of new actors and removal of old ones (Malerba, 2005b). Of particular interest in this research is to analyze how changes in the knowledge base and learning processes could induce the process of change in sectoral systems of upstream petroleum industry. Changes in the innovative behaviour of the agents and their relationship with each other are of particular importance. In addition, analysis of the role of demand in these dynamics and its transformation is important in understanding the dynamics of SIS in upstream petroleum.

The transformation of SIS is related to other concepts which need clarification, because they are used in this research. The first is Industry life Cycle (ILC) and the other is Industry Architecture (IA). In fact, ILC is often regarded as one the main intellectual roots of SIS approach, since its early conceptual development (Malerba, 2002). Particularly, attention to the dynamics and transformations of sectors and the role of innovation and technical change in industrial dynamics in SIS approach partly come from this concept. Nonetheless there are some important differences. While ILC tend to takes a *universal* and uniform approach to cyclical developments of industry, the SIS approach highlights tentative *differences* between industries created by their technological regimes like appropriability conditions and their institutional environment. These conceptual and methodological differences give privilege to SIS for the purpose of this study, although the dynamic aspect of ILC remains valid in innovation systems approaches.

ILC models are also proposed to explain cyclical regularities and industrial dynamics in parallel with the stages of PLC model, focusing on structural changes of industries in terms of number and size of the firms. In this framework, an industry is often created by a technological breakthrough within an existing industry or from other sources such as scientific discoveries (Klepper, 1997). At early stages, industry is very unstable and entry barriers are low, therefore large numbers of firms enter the industry. During the second phase when dominant design emerges, a shakeout happens as the number of entering firms decline and many firms leave the industry. A few most innovative pioneering firms and successful imitators tend to dominate the industry, thanks to increasing return to scale and become long-term survivors. Shakeout wipes out those who are unable to cope with novelties and discourage new entrants. While product innovation is dominated in early stages, it is gradually replaced with process innovation. In the maturity phase of the sector, innovation rate declines (Utterback and Abernathy, 1975).

Niosi and Zhegu (2008) proposed that two categories of variables are left unexamined by ILC models. However the advantage of SIS approach is that it puts emphasis on these two categories of variables which deeply shape cycles of industrial dynamics and are important in understanding deviations from standard ILC models. The first category is *institutions* or what Nelson and Sampat (2001) call ‘social technologies’ which include social and organizational practices and public policies. According to their view, development of industries could be better understood as co-evolution of physical and social technologies. While ILC models pay attention to physical technologies in driving industrial dynamics, they neglect the role of institutional framework or social technologies. ILC models also have not analyzed the role of characteristics of knowledge and technologies underlying different sectors as the second neglected set of variables in evolution of industries, despite innovation are the starting point of these models.

However as explained before, incorporation of both sets of variables i.e. institutions and technological regimes are the privilege of the SIS approach. At the methodological level and in contrast with ILC models, the SIS approach does not seek a uniform pattern of evolution through which all industries are supposed to proceed. Instead, it emphasises systemic understanding of the different factors that may push different industries in different directions. “One could characterize the ILC model as a search for one *universal* pattern of industrial evolution, and the SSI perspective as a tentative to underline the *differences* that institutional environments and technological developments impose to each industrial sector” (Niosi and Zhegu. 2008, p. 7). When the term ‘industry life cycle’ in upstream petroleum industry is used in this study, it does not assume the development of the industry according to standard ILC model. But, it simply refers to observed cycles of the industry evolution which does not necessarily follow the conventional model.

The Industry Architecture concept (IA) (Jacobides et al. 2006; Brusoni et al., 2009) is another notion close to the SIS approach. This concept is introduced in response to inadequacies in the conventional view of industry where the boundaries are implicitly fixed and given. Although the general questions the two concepts are seeking to answer are broadly different, they have some common methodological elements. While SIS approach is more concerned with structure and organization of innovative activities in different industries, IA focuses more on the analysis of vertical structure of the sectors in their production processes and organization of the value chains. The concept of IA is aimed to capture the rapidly changing boundaries of industries and shifting *'roles and rules'* in the course of time (Jacobides et al. 2006). The dynamics of IAs capture evolutionary changes and pay attention to the stable but evolving relationships between different players along the value chain. It seeks to understand what makes sectors swing between integration and disintegration and how knowledge integration happens in the production processes (Brusoni et al., 2009).

I use the term IA in this research to describe the evolution of the vertical division of labour among different agents in upstream petroleum industry in the next chapter. The comparison of the above definition with that provided for sectoral systems of innovation (and production) reveals several similarities. Encompassing different agents involved in a sector - as a set of related industries - and their heterogeneous knowledge and capabilities, focusing on dynamics and transformation and paying attention to the role of institutions, are the their major methodological commons. They also both pay attention to interactions between division of labour and division of knowledge in shaping industrial dynamics, although IA seems more concerned with the former. In my view, if SIS is used in its broad expression (sectoral systems of innovation and production) it covers the notion of IA. Although these commonalities provide opportunities for more integration of the two concepts, I prefer to use them separately in this research to distinguish between production chain, and knowledge and innovative activities. Of course, the relationships between the two and their interactions are recognized and acknowledged, when necessary.

Some methodological issues are implied in the application of SIS framework which I consider in relation to the case of upstream petroleum industry in this research. They include level of aggregation, geographical boundaries and product boundaries of sectoral system (Malerba, 2005b). In terms of level of aggregation, this approach is flexible about the unit of analysis at higher or lower levels of firms and other actors such as groups of firms or firms' subunits. As will be seen later, in the case of upstream petroleum industry, I used aggregated data both at sectoral level (sectoral patterns of innovation) and at the level of particular types of companies.

Likewise, geographical boundaries of sectoral systems could be set at local, national and global levels and may also change over time, depending on the objectives of the study. In upstream petroleum industry both national and global levels of analysis have been used in order to capture catch-up countries, changing relative position of different countries and dynamics of international geographical patterns of innovation. In other words, innovative behaviour of catch-up countries is analyzed. In addition, we explore the geography of innovation at global level and analyze the role of different countries in shaping global dynamics of innovation.

SIS approach is flexible in product boundaries from narrow to broad scope. The advantage of a broad definition is that interdependencies, linkages and transformations spanning wide ranges of products, processes, actors and functions are taken into account. This study applies a broad definition, covering all activities involved in exploration, development and production of oil reserves and other supporting activities classified in upstream petroleum industry. It is clear from these methodological features that SIS should not be viewed as "a rigid and closed framework, but *as a broad and flexible framework*, encompassing different elements and variables, according to the focus of analysis" (Malerba and Mani, 2009, p. 12). This study is in fact a clear example of these methodological flexibilities and its value for understanding different dimensions of sectoral dynamics.

These methodological flexibilities and dynamic, systemic and integrated perspectives have attracted many scholars to study SIS of different industries both in advanced (Malerba, 2004) and developing (Malerba and Mani, 2009) countries. This framework also proved useful to study the international performance of countries in different industries and understanding the factors behind their relative success or failures (Coriat et al., 2004). Analysis of sectoral systems could provide valuable insights for the design of technology and innovation policy at sectoral level. One main advantage of this approach for policy analysis is that it takes into account sectoral specificities and even different impacts of horizontal polices on different sectors (Malerba, 2003). This approach seems compatible with the new industrial policy approach (Rodrik, 2004, 2007) which emphasises the role of policy in provision of sector-specific public goods via relevant institutional design.

3.3. Sectoral patterns of innovation

One of the core messages of the SIS approach is that sectors differ in terms of patterns and organization of innovation. Technology related factors or technological regimes are considered in shaping sectoral patterns of innovations in different industries. This argument is supported by showing that these patterns are systematically different across technologies, but remarkably similar across countries (Malerba and Orsenigo, 1996; 1997).

A range of empirical studies has been performed in order to evaluate these ideas. The main proposition is that industries and technologies differ in terms of pattern and structure of innovative activities. Within this broad claim, two complementary aims have been followed. First, is to distinguish between different technologies and industries in terms of their patterns of innovation. The result of these efforts usually has been the suggestion of some kind of taxonomies or typologies to distinguish between structures of innovative activities in different industries. In addition, researchers tried to understand the factors which could explain these various innovation patterns across industries. In other words, “how and why innovation differs across sectors?” (Malerba, 2004, p.380). The concept of technological regimes is introduced as a set of industry specific factors to explain variation of patterns of innovation among different sectors.

Inspired by the works of Schumpeter, one of the simple but powerful and heavily researched taxonomies is the distinction between Schumpeter Mark I and Schumpeter Mark II sectors. Schumpeter identified two major patterns of innovative activities, although the labels of Schumpeter Mark I and II were coined subsequently by Nelson and Winter (1982) and Kamien and Schwartz (1982).

Schumpeter Mark I was originally introduced in *The theory of economic development* (Schumpeter, 1934). It is characterized by *creative destruction* where new firms play a major role in innovative activities and barriers to entry in technological activities are low. New entrepreneurs continuously launch new companies and bring new ideas to the sector. They may introduce new forms of production and distribution which could disrupt the established practices in the sector and wipe out the quasi rents of previous innovators.

In contrast, *creative accumulation* is the main characteristic of Schumpeter Mark II. Large established firms play major role in technological activities. It is challenging for new small innovators to enter into these industries. With regard to this new type, Schumpeter discussed the prevalence of the role of large firms and their big R&D departments in introducing new technologies in his next book , *Capitalism, socialism and democracy* (Schumpeter, 1942). Accumulated technological capabilities in large firms coupled with their production competencies and financial resources could create high barriers to entry for new firms.

These two types are also labelled as *widening* and *deepening* by other scholars who tried to find empirical verifications for these two major patterns of innovation. In a *widening* context, the innovation base of the industry is expanded by entry of new innovators while technological advantages of large firms are contentiously challenged and eroded. In contrast, the *deepening* context is characterized by the increasingly dominant role of a few large firms which accumulate innovation and technological capabilities over time. These two approaches became the subject of series of articulated empirical studies. (for example Malerba and Orsenigo, 1995; 1996; 1997; Breschi et al., 2000 among others).

One of the central concerns of economics of innovation from the beginning has been empirical evaluation of these two archetypical patterns of innovation. Malerba and Orsenigo (1995, 1996, and 1997) launched empirical investigation of the very existence of these two patters of innovation, while they extended the notion of Schumpeterian patterns of innovation at the same time. They explored the two patterns of innovation based on four indicators. Concentration and asymmetries (captured by the Herfindahl index) of innovative activities within firms, innovation size of the firms, stability of the ranking of innovators over time, and relative share of new innovators in comparison with the incumbents are the four indictors to distinguish between the two archetypical patterns of innovation in different sectors.

As these indicators are used in the chapter 6, I briefly introduce them. The first indicator was suggested to understand whether innovations are concentrated within a few firms or distributed more evenly among large number of firms. The second is meant to explore whether small firms or large firms produce the bulk of innovation in any industry or technological area. These are the two traditional indicators which are usually used in the analysis of the so called Schumpeterian hypothesis. The third indicator is aimed to capture the degree of stability or, turbulence in the innovation system. High stability is interpreted as the dominance of creative accumulation and low stability and high turbulence is an evidence for the dominance of creative destruction. The statistical analysis of these indicators produced quite reliable results, finding a meaningful relationship observed within these variables on the one hand, and distinguishing two archetypical Schumpeterian patterns of innovation on the other (Malerba and Orsenigo, 1995; 1996; 1997; Breschi et al., 2000).

According to these four indicators, Schumpeter Mark I industries are defined as low concentration, small innovation size, and low stability in the ranking in conjunction with high new entries. Conversely, high concentration of innovative activities, large innovation size, high stability and low new entries characterize Schumpeter Mark II sectors. The two models could also discriminate empirically between traditional industries with characteristic pattern similar to Mark I, while modern industries like chemicals and electronics were found more similar to Mark II (Malerba, 2007).

Two other important conclusions are drawn from the *cross-sectoral* comparison of Schumpeterian patterns of innovation in different technological classes. First, it is concluded that Schumpeterian patterns of innovations are technology or industry specific, because of the observation of strong similarity in the same technology class across countries. It suggests that some common features of technological environments could largely be responsible for the formation of patterns of innovation. These features of technological environment which are labelled as *technological regimes* are considered relatively *invariant* with respect to other features of the environments such as prices. Second, despite the existence of these similarities across countries, country level variations in the same technological class are also sometimes quite significant. This is suggested to be the impact of particularities of national systems of innovation, their historical and institutional environment, or some special historical background of firms or industries (Malerba, 2007).

Although this line of research achieved very important results, the findings suffer from two limitations. First, the methodology used does not allow for the observation of variations *within* technological classes and industries, because of the analysis at aggregated levels. Rather it forces every technological class or industry to be dropped just into one of the archetypical patterns of innovation. There is no theoretical reason to constrain thinking about the existence of combinations with both patterns in some industries. Second, the methodology employed does not allow for the observation of *temporal variation* in sectoral patterns of innovation within industries, simply because the time dimension is removed. Although authors clearly accept that the patterns of innovation may have changed over time, they again assume an average behaviour over the time for every single technology class (Malerba and Orsenigo, 1996).

These limitations and assumptions have been addressed in more recent studies, but this gap is yet to be covered by more comprehensive studies. For example, Corrocher et al. (2007) observed the co-existence of both Schumpeterian patterns of innovative in ICT industry. Grebel et al (2007) also provided similar evidence, arguing the co-existence of large diversified and new technology firms within innovation networks in knowledge intensive industries like biotechnology and telecommunication. They actually emphasised the critical function of innovation networks which combine both "entrepreneurial and managerial routs to innovation, or as Schumpeter Mark I and II" (Grebel et al, 2007 p.66) for creation and diffusion of new knowledge in the knowledge economy. In their view, both patterns could be seen as complementary where new technology firms contribute in technical knowledge; while large firms are important in provision of organizational and market knowledge.

Malerba and Orsenigo (1996) suggested the study of "changes in Schumpeterian patterns occurring during a technology and an industry life cycle" (P. 470) highlighting the importance of second limitation in the literature. In other words, *inter-temporal* shifts in sectoral patterns of innovation is considered as an under researched issue. In the next article, they elaborated more, acknowledging the possibility of change in the nature of technological regimes over the course of time. "Some of these features of knowledge *may change* during the evolution of a specific sector or technology (degree of codification, independence, and *complexity*)" (Malerba and Orsenigo, 1997. p. 97 emphasis added).

In a "theoretical-appreciative discussion" a few years later, they tried to push the boundaries of the research further linking technological regimes and patterns of innovation with a dynamic flavour. They concluded "... discussion of the relevant dimensions of knowledge ... are necessary for an understanding of innovative activities at sectoral level and their links with *industrial evolution*" (Malerba and Orsenigo, 2000. p. 311, emphasis added).

Nevertheless, this *dynamic* and *inter-temporal* approach to the nature of technological regimes and its possible association with evolution of sectoral patterns of innovation seems still to remain at the level of "theoretical-appreciative discussion" (Malerba and Orsenigo, 2000. p. 311). Later in a review article about innovation and industry evolution, Malerba (2006, p. 14-15) concluded that "change in knowledge and knowledge base… goes to the *heart* of the evolution of the industries and of the factors affecting the change in industrial structure" (emphasis added). To the best of my knowledge no empirical quantitative study has addressed this relationship in an *inter-temporal* mode of analysis, some years after *cross-sectional* studies provided empirical evidence[12].

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[12] There are some valuable attempts to model the industry evolution and dynamics using history friendly (Malerba et al., 1999; Malerba et al., 2001, Malerba and Orsenigo, 2002; Malerba et al., 2008) and agent-based models (Pyka and Fagiolo, 2005) drawn from complexity theories. What is more missing is empirically grounded studies which analyze the dynamic relationship between technological regimes and sectoral patterns of innovation using quantitative methods.

It is helpful to understand why this dynamic approach remained underdeveloped, in spite of repeated reminders about its importance and its methodological consistency with SIS approach. There are some possible ideas. First, although it is theoretically accepted that technological regimes and sectoral patterns of innovation may change over time, the concepts are often operationalised as a static variable. By definition, technological regime is usually considered as an *invariant* variable. This simply resulted in the prevalence of framing of the inter-sectoral questions instead of inter-temporal inquires.

Second, change in patterns of innovation and technological regimes may take long periods of time and therefore it require long time-series. Until recent times, these kinds of longitudinal data have not been easily available. In fact for the short time periods in which previous studies were designed, it was reasonable to assume that technological regimes and patterns of innovation have been constant. Third, it might not be analytically easy to tease out these dynamic and co-evolutionary relationships. “This is a *very difficult* task to accomplish, even for a *single case study*, let alone the identification of regularities and laws of knowledge change in sectors” (Malerba, 2006 p. 14-15, emphasis added).

Given the lack of these kinds of dynamic quantitative studies in SIS literature, we extend this line of reasoning by introducing a dynamic mode of analysis. This mode of analysis could unravel the organizational implications of change in technological regimes over time. The focus of this thesis however is on dynamics of knowledge base complexity, among other dimensions of technological regimes. This mode of analysis requires a dynamic reading of the concept of technological regimes, not to be considered as an invariant variable in long run. Rather, the methodology should be designed in a way to capture the dynamics of technological regimes and knowledge complexity. The next section reinterprets the concept of technological regime in a dynamic approach.

3.4. Technological regimes in dynamic perspective

I have already defined the concept of technological regimes at a general level, as one of the core concepts which SIS literature suggests to explain variation of sectoral patterns of innovation in different industries. In this part I describe the background of the concept and its main elements in the literature and how it could be viewed as a dynamic concept. If technological regimes are to be accounted as a variable over time, we need to understand how and why different elements of technological regimes may change over time. This dynamic reading of technological regimes allows exploring dynamics of knowledge base complexity as one of constituents of technological regimes and associated dynamics in sectoral patterns of innovation.

The notion of technological regimes was first introduced by Nelson and Winter (1982) referring to the knowledge environment in which firms operate, or in which their problem-solving activities take place (Winter, 1984). They distinguished between science based and cumulative regimes, defined by their particular opportunity and appropriability conditions. The idea of technological regimes was further developed by Malerba and Orsenigo (1990, 1993) and was introduced as a synthetic concept constituted of several elements. In a more operational form, four main elements have been suggested which their combination defines different technological regimes. They include technological opportunity, the appropriability of innovations, their cumulativeness, and knowledge base properties (Breschi et al., 2000; Breschi and Malerba, 2000).

The ‘Properties of knowledge’ base which refers to characteristics of knowledge underlying innovative activities is itself a synthetic construct encompassing the degree of specificity, tacitness, ‘*complexity*’ and independence (Breschi et al., 2000). This is where SIS is directly connected to the topic of this thesis, because knowledge base complexity, alongside other elements of technological regimes, is considered important in defining sectoral patterns of innovation.

Technological opportunities refer to the likelihood of innovation in a particular sector resulting from a given amount of money invested in search processes. An industrial environment characterized by high technological opportunities provides strong incentives for innovation. As a result, firms and other actors may come up with higher investments in innovation and frequent technological breakthroughs (Breschi, et al., 2000). Industries considerably differ in terms of their technological opportunities and the rate of technological progress. Some industries express rapid technological progress, while others are relatively slow in terms of innovation. According to Klevorick et al. (1995: 186-188), technological opportunity determines “the productivity of R&D” or “the set of possibilities for technological advance.” The concept was proposed to explain the different R&D intensity and technological progress in various industries based on the nature of technology.

Technological opportunities stem from three main sources. However the level and significance of these sources may vary in any particular industry. First, the pool of technological opportunities may be expanded based on progress in scientific knowledge and techniques. Second, technological developments in other industries could contribute to technological opportunities. Third, positive feedbacks of technological opportunities in terms of resources could contribute to technological opportunities in subsequent periods (Klevorick et al., 1995).

Given that each of these three sources may change over time, it is clear that technological opportunities could be defined as a dynamic concept. Over the life cycle of the industry, technological opportunities may significantly change. The standard ILC model assumes that opportunity conditions are depleted when industries get mature (Klepper, 1996). However, some empirical statistical analysis (McGahan and Silverman, 2001) case studies in mature industries (Acha and Brusoni; 2005) and research on innovation in low- tech industries (Robertson et al., 2009 & 2007; Mendonça, 2009; Hirsch-Kreinsen, et al., 2006; Von Tunzelmann and Acha; 2005) show that this is not necessarily the case. In other words, no simple relationship between industry life cycle and technological opportunities could be established. Technological opportunities could be influenced by multiple interactive factors. I analyze the dynamics of technological opportunities in upstream petroleum industry in chapter 6 and provide some explanations for the dynamics of observed pattern.

Appropriability of innovations reflects the possibility of protection of innovation from imitation through various strategies to pay off the costs and earn profits. If these protection strategies could be effectively exercised, industries have high appropriability conditions. In contrast, appropriability would be low if there are widespread spillovers and there is no effective compensation mechanism. Companies employ different range of strategies to capture the benefits of their innovations. They include patent or other intellectual properties, vertical integration and control of complementary assets, or even shaping the ‘industry architecture’ (Teece, 1986; Levin et al.; 1987; Jacobides et al. 2006; Pisano and Teece, 2007).

This dimension of technological regimes also could be viewed as a dynamic concept. The level of appropriability could be seen as a function of firm’s strategies (like choice of patent or secrecy), their environment (such as patent laws and regulations), and nature of knowledge to be protected (such as tacitness). As a result, the level of appropriability of innovations in an industry might vary from time to time depending on change in these factors.

Cumulativeness captures the degree to which today’s available knowledge and innovative activities form the foundation of future innovations. A high degree of cumulativeness creates some kind of path dependency and imposes challenges for jumping the stages of technological development. Cumulativeness and path dependency could appear at different levels. At the technological level it refers to the cognitive features of a particular technological domain and learning processes involved in that field. Cumulativeness at firm level arises when a continuous stream of innovations relies on competencies of specific firms. For example costly innovation processes, indivisibility of R&D projects and cognitive interdependencies between different technological domains or segments of the industry create advantages for large firms. This leads to higher barriers to entry for newcomers or small players. When the relevant knowledge base of a sectors is widely available for industry participants but not for outsiders, sectoral or industrial level of cumulativeness are present. Finally, if the stream of innovations depends on innovative capabilities of firms located in particular geographical territories (regions, countries, and so on), cumulativeness appears at a geographical level (Breschi, et al., 2000).

Cumulativeness also may change over time and therefore could be conceptualized as a dynamic concept with temporal dimension. The literature on technological and industrial discontinuities (Tushman and Anderson, 1986) and technological paradigms (Dosi, 1982) have documented shifts in cumulativeness over time and the implications for industrial organization in the sector. Studying technological discontinuities in three industries, Tushman and Anderson (1986) found two important classes of technological continuity. ‘Competence-enhancing’ discontinuities emerge where the industry experiences a radical innovation, yet largely based on existing accumulated knowledge. On the other hand, ‘competence-destroying’ discontinuities similarly introduce significant technological novelty to the sector, but based on knowledge and skill which are new to the sector and largely different from prior know-how. “While competence-enhancing discontinuities build on existing experience, competence-destroying discontinuities require fundamentally new skills and technological competence. (p. 460)” As a result, competence-enhancing discontinuities are associated with higher knowledge cumulativeness which tends to favour incumbent firms. Competence-destroying discontinuities, by definition, reduce or remove the knowledge cumulativeness. Consequently, they tend to favour new firms equipped with new technical competences which are dissimilar to the previous knowledge of the sector. This situation may offer opportunities for leapfrogging in catching-up countries, because there is not much advantage for incumbents compared to newcomers (Perez and Soete, 1988).

Knowledge base properties: The degree of *specificity*, *tacitness*, *independence* and *complexity* are main properties of the knowledge base which are discussed in the literature of technological regimes (Breschi and Malerba, 2000). *Specificity* refers to the scope of applications of particular knowledge domain. *Tacitness* refers to the extent to which knowledge is not articulated in standard formats such as blue prints. Degree of *independence* which is often defined versus systemic knowledge base refers to the extent that relevant knowledge to the innovative activities could be easily isolated.

Like other dimensions of technological regimes, these properties of the knowledge base could also change over time. The degree of specificity may change as available knowledge find new applications and inter-industry knowledge flows increase. Degree of tacitness also may change as a result of codification practices over the technology life cycle, new instrumentation and computational capabilities (Arora and Gambardella, 1994) or facilitation of ICT (Steinmueller, 2000).

The main point for this dynamic reading of different dimensions of technological regimes is the possibility of significant change over time. Therefore, we could reasonably expect the dynamics of sectoral patterns of innovation to present some kind of association with the dynamics of technological regimes. This is in fact the dynamic extension of SIS approach where the concept of technological regimes is perceived as an important determinant of sectoral patterns of innovation. This could be seen as the overarching or grand hypothesis of this research. We aim to examine this broad idea in upstream petroleum industry at three sectoral, organizational and geographical levels, but with particular focus on knowledge base complexity among other dimensions of technological regimes.

3.5. Literature gap: dynamics of knowledge base complexity

The *complexity* of knowledge base is the particular dimension of technological regimes with which I am most concerned in this research. From the perspective of literature on technological regimes (Malerba and Orsenigo, 1997; Breschi and Malerba, 2000), a knowledge base is defined as complex if (a) it involves integration and combination of different scientific and technological disciplines and (b) requires a variety of competences (such as R&D, design and engineering, manufacturing, production and marketing) for innovative activities.

Given the definitions provided, a close relationship between complex (vs. simple) and systemic (vs. independent) could be understood. The more systemic a knowledge base is, the more difficult to isolate the impacts of different parts of the system. Therefore innovation process requires access to and integration of different knowledge sources, wider competences and technological capabilities. This means that the underlying knowledge base is also complex. Due to this conceptual closeness, I use the term complexity in a broad sense which also captures the systemic nature of the knowledge base. This issue will be addressed in more detail in chapter 5.

Although knowledge base complexity is introduced as one of the important dimensions of technological regimes in the SIS approach, it is almost neglected in subsequent empirical research. Within the dynamic interpretations of technological regimes presented in previous sections, this section calls for the analysis of the relationship between the dynamics of knowledge base complexity and patterns of innovation. In fact, the topic is at the intersection of two main gaps explored in the literature. On the one hand, there is the missing dynamic mode of analysis in the literature as explained in the previous section. On the other hand there is the lack of enough attention to the role of knowledge base complexity, compared to other elements of technological regime. This is of particular importance in the context of latecomer countries where complexity could prevent technological catch-up. In addition, some conceptual ambiguities and theoretical inconsistencies in the analysis of geographical implications of complexity suggest an attractive space for academic contribution. Summarising the relevant research about dynamics of knowledge complexity, this section shows how this issue is relatively neglected in the literature.

From previous research (Malerba and Orsenigo, 1997; Breschi et al., 2000) we know that technological regimes provide satisfactory explanation for *cross-sectional* variation of sectoral patterns of innovation. Theoretically, we also expect *inter-temporal* variation of sectoral patterns of innovation associated with dynamics of technological regimes. Nonetheless, previous empirical research has only shown that a *static* relationship between technological regimes and sectoral patterns of innovation in cross-sectional studies is statistically significant. Quantitative and statistical analysis of the dynamic relationship between technological regimes and patterns of innovation has been largely neglected in previous research.

Theoretical relationships between different dimensions of technological regimes and Schumpeterian patterns of innovation have been widely discussed in the literature (Malerba and Orsenigo, 1995; 1996; 1997; Breschi et al., 2000). From the analytical point of view, each dimension of technological regime could have particular impact on patterns of innovation. For example, ceteris paribus, a high degree of tacitness could lead to high concentration of innovation in some industries, because it limits knowledge spillovers to other firms. However, in reality different combinations of various dimensions of technological regime (opportunities, appropriability, cumulativeness, tacitness, complexity, and so on) could create different patterns of innovation.

Previous studies established the relationship between technological regimes and patterns of innovation in an inherently static research design. This approach is not able to explore the dynamics of technological regimes and the associated sectoral patterns of innovation by definition. Nonetheless, there is now a priori theoretical reason that we could not expect the relevance of dynamic conceptualization of this relationship. In other words, if one or several dimensions of technological regimes change over time, they are very likely to shape the ways in which firms organize their innovation processes. For example if codification of knowledge reduces the degree of tacitness and therefore facilitates knowledge transfer, we expect innovation processes to become more distributed.

In addition to this static mode of analysis, partial coverage of technological regimes is another limitation in current statistical studies (Malerba and Orsenigo, 1995; 1996; 1997; Breschi et al., 2000). While technological opportunities, appropriability and cumulativeness of knowledge are included in the analysis, tacitness, independence and *complexity* are often excluded. This could be attributed to the lack of reliable data and relevant proxies to capture these elements. In particular, the role of knowledge base complexity has not been addressed. This gap offers an attractive area for contribution. We need to understand how change in technological complexity might alter the patterns of innovation. This dynamic approach could have important strategy and policy implications, as both firms and governments need to adapt their approaches and decisions according to the relevant changes in the nature of technology.

Although, this kind of dynamic approach is largely missing in quantitative and statistical studies, some qualitative case studies (Vale and Caldeira, 2008, Iizuka, 2009) have recently taken a dynamic approach. The dynamics and transformation of sectoral systems are analysed based on changes in knowledge complexity. These qualitative studies could provide valuable insights and a clue for the formulation of relevant hypothesises. For example, the analysis of the footwear industry has shown how transformation of the traditional knowledge base of the sector to a complex system changed the organization of innovation. Driven by fashion and increasing importance of design, this knowledge complexity shaped more complex organization of innovation associated with increasing tacitness, cumulativeness and appropriability (Vale and Caldeira, 2008). Similar dynamic approaches have been recently also applied in the context of developing countries (Malerba and Mani, 2009). The relationship between change in the knowledge base and organization of innovative activities are addressed in evolution of salmon farming industry in Chile (Iizuka, 2009). Although these studies address the transformation of patterns of innovation in relation with change of technological regimes, our understanding of these industrial dynamics are still limited.

This research aims to contribute in this gap in three ways. The first contribution is conceptual and theoretical. Among other elements of technological regimes, complexity has not been addressed in quantitative studies mentioned above - even in existing inter-sectoral research - although it has recently gained the attention of scholars both in economics (such as Beinhocker, 2006) and economics of innovation (such as Antonelli, 2011). In addition, there are some conceptual ambiguities about the definition of complexity, and theoretical inconsistencies about its impacts in the literature, which will be explained in chapter 5 and 7. I propose that a dynamic and three-dimensional perceptive to knowledge base complexity which distinguish between breadth, depth and systemic complexity could resolve some of these issues.

Second, this study proposes a quantitative methodology for exploration of the dynamics of knowledge base complexity and patterns on innovation and the possible links between the two. In fact this is an extension of available static methods discussed above into inter-temporal analysis. In other words, I examine whether statistical quantitative methods which are employed in inter-sectoral studies could also reveal the association between dynamics of knowledge base complexity and patterns of innovation. The final contribution of this research is empirical. This research is an attempt to apply the suggested methodology and conceptualization to the case of upstream petroleum industry, as a relevant case.

3.6. A dynamic perspective to geographical patterns of innovation

In parallel to early developments in the analysis of relationships between technological regimes and sectoral patterns of innovation, discussions about geographical aspect of innovation patterns have also been on the research agenda. I have already mentioned in section 3.4 that cumulativeness could occur at local level due to geographically bounded externalities and creation of self-reinforcing mechanism which promotes spatial clustering (Breschi, 2000). In addition, effective knowledge exchange over distance could vary, depending on the properties of the knowledge base and their influence on the ways in which firms organize the spatial boundaries of their innovative activities (Breschi and Malerba, 2000).

Some studies have explored the link between sectoral patterns of innovation and international technological specialization providing supporting evidence (Malerba et al., 1997; Cefis and Orsenigo, 2001; Malerba and Montobbio, 2003). The application of SIS framework has been recently extended to the analysis of catch-up processes highlighting the importance of sectoral differences in catch-up strategies (Malerba and Nelson, 2010, Kim, Lee, 2008). In other words, sectors may differ in their potential for catch-up, as their learning and technology regimes may or may not be in favour of newcomers. Broadly speaking, what is common in these studies is their direct or indirect claims about possible links between technological regimes and geography of innovation. In other words, it is assumed that technological regimes could be an important factor in shaping geographical patterns of innovation.

Breschi (2000) is a key study in addressing the theoretical relationships between each individual dimension of technological regimes and its geographical implications. His central claim is that technological regime does not only affect the way in which innovative activities are organized at sectoral level; it could have important consequences for the organization of innovative activities at spatial and geographical levels. In other words, learning, innovation and competition processes may occur among regions and countries in which companies are located. Therefore, there could be a close relationship between sectoral and geographical patterns of innovation. Similar to archetypical Schumpeterian patterns of innovation, two archetypical spatial patterns of innovation are introduced. They are high and persistent concentration (or concentrated) vs. low concentration (diffused) at geographical level. Each is expected to emerge under different technological regimes. The empirical findings support that technology specific factors (i.e. technological regimes) play a key role in shaping geographical patterns of innovation.

Similar to sectoral patterns of innovation, such a theoretical relationship between technological regimes and geographical patterns of innovation is also expected to be valid inter-temporally. If the combination of dimension of technological regime changes fundamentally over time, relevant and consistent changes at geographical level are also expected. For example, if cumulativeness of technologies is reduced, we expect to observe lower geographical concentration of innovative activities.

There are several studies which document fundamental transformations of knowledge bases of different industries: both traditional sectors such as footwear (Vale and Caldeira, 2008), tyre (Acha and Brusoni, 2005), salmon farming (Iizuka, 2009); and, modern sectors such as pharmaceuticals, chemicals, telecommunication equipment and services, and software (Malerba, 2005b). Nonetheless, the reflections of these changes in the knowledge base are studied more at a sectoral level and very rarely at a geographical level, either nationally or internationally.

Vertova (2002) is an exception, dealing with historical changes in the geography of innovation in different sectors. In her analysis, geographical concentration versus diffusion are analysed in both innovation growing and declining sectors. Four different technological trends are explored. In her terminology, a *technological leadership* trend is characterised by geographical concentration of innovative activities in high innovation growth sectors. This trend is explained based on supportive national innovations systems in particular countries. By contrast, innovative activities of low innovation opportunities sectors may become geographically concentrated in *country specific trends* due to specific geographical relevance of those sectors. A *technological pervasiveness* trend is associated with geographical diffusion in high growth sectors. It emerges due to widespread application of general purpose technologies in many industries. Conversely, a *technological maturity* trend is the feature of low opportunity sectors which have become available to many and therefore express geographical diffusion. She emphasises that both country related and technology related factors could be influential in changing geographical patterns of innovation, but she does not go into detailed analysis of these dynamics in different sectors.

With particular focus on complexity among other dimensions of technological regimes, the present study aims to explore the association between the dynamics of knowledge base complexity and geographical patterns of innovation. This particular choice has mainly a theoretical reason. From a theoretical point of view, it seems that increasing complexity of the sector is one of important cognitive barriers for entrance of companies from late comer counties, although high technological opportunities could potentially offer knowledge based path to industrial development. On the other hand, greater technological complexity could also force companies to disperse their innovative activities globally in order to get access to advanced knowledge produced in globally distributed centres of excellence (Athreye and Cantwell, 2007). These geographical aspects are discussed in chapter 7.

3.7. Conclusion

In this chapter Sectoral Innovation Systems (SIS) is introduced as the broad analytical framework of this study with the capacity to address the role knowledge base complexity in dynamics of patterns of innovation. Technological regimes and sectoral Schumpeterian patterns of innovation are described as the main theoretical concepts in the SIS approach. Their relationship has been the subject of theoretical analysis and empirical examination. Empirical evidence has broadly supported the critical role of technology and knowledge related factors in shaping Schumpeterian patterns of innovation.

In spite of the relative success in dealing with the relationship between technological regimes and sectoral patterns of innovation at conceptual and empirical levels, two important aspects have been relatively neglected. First, almost all quantitative empirical studies have taken an inter-sectoral design assuming technological regime as a time-invariant variable. Nonetheless, it is broadly accepted in the SIS approach that both technological regimes and sectoral patterns of innovation could, in principle, change over time. In fact, this dynamic perspective and attention to the transformations of sectoral systems over time has been introduced as one of the methodological benefits of the SIS approach, although it is somehow neglected in subsequent quantitative studies.

Second, knowledge base complexity is an under researched element of technological regimes from both conceptual and empirical aspects. Although conceptually, a dynamic reading of all elements of technological regimes is presented, the focus of this research is on knowledge base complexity. This is mostly because of its theoretical relevance to the questions of this research on the one hand, but also due to the lack of deep understanding of the role of complexity in shaping patterns of innovation on the other. I think knowledge base complexity requires special treatment in academic debates around SIS. Not only are there conceptual ambiguities and theoretical inconsistencies about the role of knowledge base complexity in patterns of innovation. It is also a relatively neglected element, even in existing empirical inter-sectoral studies of the relationship between technological regimes and patterns of innovation.

In order to show the broad relevance of the SIS approach for this study, a dynamic reading and interpretation of different elements of technological regimes and sectoral patterns of innovation are provided in this chapter. In addition, it is mentioned that geographical patterns of innovation could have close connections with technological regimes and be framed in a dynamic view. In other words, change of technological regimes over time could have implications for and reflections in both sectoral and geographical patterns of innovation. The dynamics of geographical patterns of innovation is important to be understood, because the aim of this research is to explore catch-up processes in upstream petroleum industry and their possible connection with dynamics of technological complexity.

The review of present studies about relationship between technological regimes and patterns of innovation in sectoral innovation systems, presented in this chapter, shows that this study could extent SIS research in two important aspects. First, it is a new attempt to extend the quantitative methods used in inter-sectoral studies of the relationship between technological regimes and patterns of innovation in inter-temporal dynamic mode of analysis. This enables us to better understand the evolution and transformation of sectoral innovation systems. Second, the role of knowledge base complexity, as one of the less studied dimensions of technological regimes in shaping the dynamics of sectoral innovation systems, is deeply explored.

Furthermore, industry life cycle (ILC) and industry architecture (IA) are introduced in this chapter, as two related concepts to SIS. I clarified in which sense they are used in this thesis and how they differ from the SIS approach. While ILC in its conventional sense tends to propose similar trajectories for all industries, SIS puts emphasis on the importance of differences among industries in terms of their learning regimes and patterns of innovation. The notion of Industry architecture (IA) is another related and overlapping approach to SIS describing changing vertical division of labour over time.

The aim of this chapter was to introduce the literature background and the main concepts used in this research. This chapter not only revealed the gap in SIS research, it also provided a template in which all subsequent chapters are located and their relationship is clear. The next chapter can be seen as the twin of this current chapter where the key features and dynamics of upstream petroleum industry are introduced using sectoral systems and industry architecture concepts. The dynamics of knowledge base complexity of upstream sector is addressed separately in chapter 5, because it is a core concept of this research. Sectoral and geographical pattern of innovation are the subjects of chapters 6 and 7 respectively. Chapter 8 combines the results and summarizes the main conclusions of the research.

4. Chapter 4: Sectoral innovation systems of upstream petroleum industry

4.1. Introduction

When Colonel Drake was drilling the first oil hole in 1869 in Pennsylvania (Babusiaux et al.; 2004 pp. 6), he never imagined he was launching a new era. An industry emerged which for some became a nice blessing, but for others brought curse (Stevens, 2003). The modern industrial era was built upon this black gold as the source both of energy and raw material for many economic activities. Its supply security became one of the main concerns of the international community. This is why the struggle for oil has been a source of many wars (Babusiaux et al.; 2004 pp. 4; Kaldor, 2007).

Although petroleum has been introduced "as necessary to the economy as blood to the human body" (Babusiaux et al.; 2004 pp. 4), the industrialization experience of some countries like Japan and Korea shows that what matters is not necessarily oil ownership, but control over its supply. On the other hand, the resource curse story (Stevens, 2003) suggests that this industry can be the source of many misfortunes, if not managed properly. Nonetheless, some of today's advanced countries have benefited hugely from their oil reserves. The benefits are not limited to enormous revenues, but include that industrial and technological capabilities emerged out of this industry and spilled over to other parts of the economy (Wright and Czelusta, 2004).

Technological innovation has been proved to be a sustainable source of competitiveness and economic growth. This is not just the case for modern sectors, but equally important for so called 'mature' or resource based industries like the petroleum industry. If the natural resource based countries are to enjoy the long term benefits of their resources, it is necessary to revise the conventional view of resource industries and understand their capacity for innovation and technical changes. This is the core message of the 'knowledge' or 'learning' approach to natural resources industries, as explained in the chapter 1. This chapter applies a sectoral innovation systems framework to the upstream petroleum industry and articulates the main drivers of innovation in different periods. The information provided is largely from secondary sources and published articles, although innovation trends, major innovative players and the knowledge base of the industry is analysed according to the patent data that I have collected.

After a brief historical background in section 4.2, the main characteristics and value chain of the industry are introduced in sections 4.3 and 4.4. Next, a broad picture of the dynamics of upstream industry architecture (IA) is presented in section 4.5. I explain how the roles of different types of players have been defined and have evolved and emphasise the main driving forces behind the evolution of the industry.

In section 4.6, I focus on the transformation of the sectoral innovation system (SIS) of upstream petroleum. The aim is to explain the dynamics of innovation over different periods and the consequences of technological innovation in the sector. In addition, the knowledge base of the industry is explored and the main actors involved in innovation processes introduced.

We find that the systemic and dynamic nature of SIS/IA frameworks provide a more comprehensive picture of industry evolution which the standard industry life cycle model is unable to show. The SIS approach captures both supply and demand factors and their evolving interaction, combined with industry architecture dynamics to analyse the industrial dynamics of the sector. We found that the upstream petroleum sector has gone through three main phases of transformation. These can be distinguished by different industry architectures and innovation systems. In addition, the analysis confirms the contribution of advances in scientific and technological knowledge and industrial innovation in development of the knowledge base. The main innovators are major players from within the sector, confirming this sector as an active and dynamic SIS which does not fit into the standard industry life cycle model.

4.2. Historical background[13]

Historically, the Standard Oil Company dominated the American oil market from its creation in 1870 until 1911. A vertically integrated strategy, from upstream to downstream, was the tool used to control this profitable business. This legacy was an important barrier to easy entry of new companies. Large financial obligations created an oligopolistic market structure first in US and then at international level. However,

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[13] This historical background is largely drawn from Babusiaux et al (2004)

Standard Oil was broken into smaller companies (New Jersey as Esso then Exxon; New York as Mobil; California as Chevron) following US antitrust policy. Together with four other newly created companies (Texaco, Gulf, Royal Dutch Shell and Anglo-Persian which later became BP in 1951), they formed 'majors' controlling a majority of the world oil production chain. The term '*seven sisters'* were coined to describe the close relationships between these Anglo-Saxon companies. Their hegemony came to an end in 1980s after more than half a century, when national oil companies emerged and upgraded their position [14] (Acha, 2002).

The Great War taught some governments how important oil independence was for victories in international affairs. Anglo-Persian and Royal Dutch Shell were key for energy independence in British and Netherlands governments. Similarly, the French government established CFP (Compagnie française des pétroles), later named Total in 1991(Babusiaux et al.; 2004, p.17). After the Second World War, some other European countries continued to establish their own government backed oil companies to secure their energy independence. ENI in Italy, ELF as the second national French oil company were two examples. IFP[15] also was established in France in 1944 seeking long-term oil independent by training, R&D and production of knowledge, technology and equipment.

From the late 1940s, the relationship between international oil companies and producing countries began to change as a consequence of the Second World War. Under pressure for a greater share of national wealth, Iranian petroleum was nationalized in 1949. Intensive competition and over supply of crude oil pushed down oil prices in late fifties. This triggered the establishment of OPEC[16] in 1960 by the main producing countries to restore declining oil prices. In addition, other political and economic events such as oil nationalizations in other Arab countries, the Six Day War, increasing oil consumption, and widespread concerns about world limited reserves prepared the scene in the sixties and early seventies for the first oil shock in 1973. The Iranian revolution in 1979 was the main source of the second oil shock which was exacerbated and continued by the

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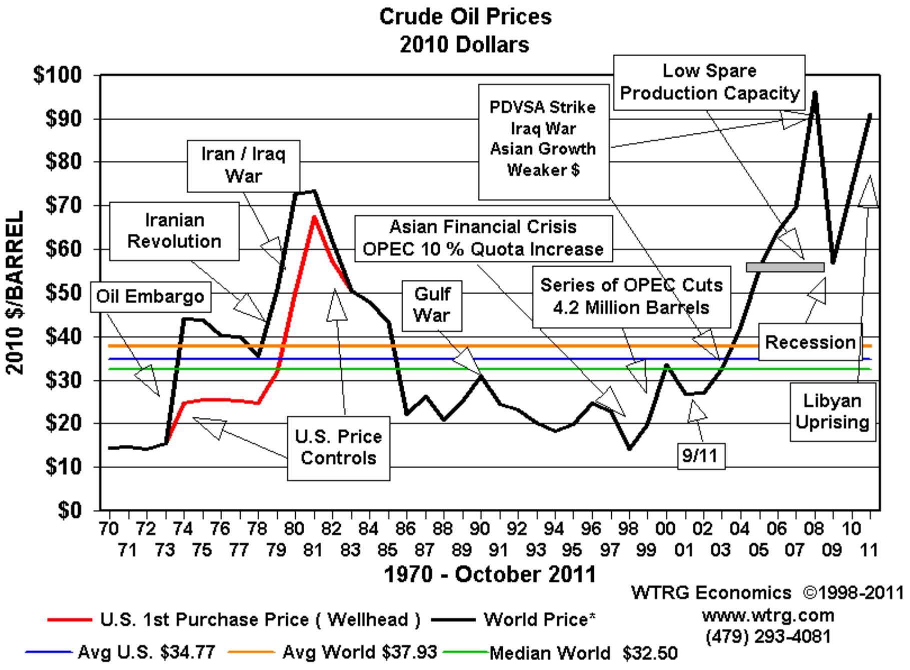
[14] For more information about history of seven sisters see: http://en.wikipedia.org/wiki/Seven_Sisters_%28oil_companies%29

[15] Institut français du pétrole

[16] Organization of the Petroleum Exporting Countries

Iran-Iraq war in 1980s pushing oil prices up to $38/bbl. The trend of oil prices after 1970 and the main influential factors is shown in the figure 4.1.

Figure 4-1 Crude oil prices (based on 2010 adjusted dollar for inflation)



Source: http://www.wtrg.com/prices.htm Access on 17th January 2012

Continued high oil prices and political instability in the Middle East encouraged western and other countries to diversify their supply sources. Concerns of scarcity and high oil prices also increased R&D investments making extraction from high exploitation-cost fields in harsh environments and deep offshore economically feasible. A counter shock happened in 1986 as a result of unilateral decision of Saudi Arabia when so-called 'net back contracts' were introduced. Although this decision was abandoned soon by OPEC, it was not very effective due to the increasing share of non-OPEC producing countries. This structural balance stabilized low oil prices for nearly two decades, in spite of short time fluctuations. Technological innovation in upstream petroleum industry became a key to bring challenging reservoirs into stream, particularly in deep offshore.

After the turn of the century, oil prices began to increase again relatively rapidly, except for a short period driven by the financial crisis in 2008. There are good structural reasons to expect that this increase will last into the medium to long term. The main driver is suggested as increasing demand in big industrializing countries such as China and India. While there are structural limits on the supply side, these countries have rapidly expanded demand due to high economic growth rates. This is not limited to petroleum but applies to most commodities and resources (Kaplinsky and Morris, 2009; Farooki and Kaplinsky; 2011). This short history of the industry shows the high level of volatility and great involvements of politics and government policy. This historical perspective is helpful to explain the dynamics of innovation in the sector, as will be shown in the section 4.6.

4.3. Industry characteristics

Upstream petroleum projects have three main characteristics which influence industry structure. (1) They are highly capital-intensive (2) They are very long lasting in terms of investments and revenues and (3) They involve various kinds of technical, economic and financial, political and environmental risks. Partnerships among operators are efficient means of allocating resources enabling trade-off between meeting scale economy and high risk (Isabelle, 2001)

In addition, the industry has a strong geopolitical element, because reservoirs are not uniformly distributed in the globe (Acha, 2002). It also involves considerable politics with high degrees of government intervention in most countries. This is because the sector is intertwined with the rest of the economy and instabilities could distort the operation of the economy. Due to the volatility in oil and gas prices, the industry also experiences cyclical conditions, and booms and busts are major features of this industry.

4.4. Industry value chain

The petroleum industry has a relatively long and complicated value chain. This begins with exploration and production of crude oil, continues with transport, refining and finally ends with retail distribution of oil products. Each segment itself could be disaggregated into more detailed activities which involve different ranges of players. Although the term petroleum industry is popular, this business covers production of both oil and gas, as they are usually discovered together with the same producing companies. The *upstream* petroleum industry, the focus of this research, comprises a set of related activities. It covers activities related to oil and gas exploration (and other similar materials such as heavy oil, condensates and tar sands), developing the reserves for extraction, production over their lifetime and finally decommissioning after depletion. It also includes the business activities supporting and supplying these main activities.

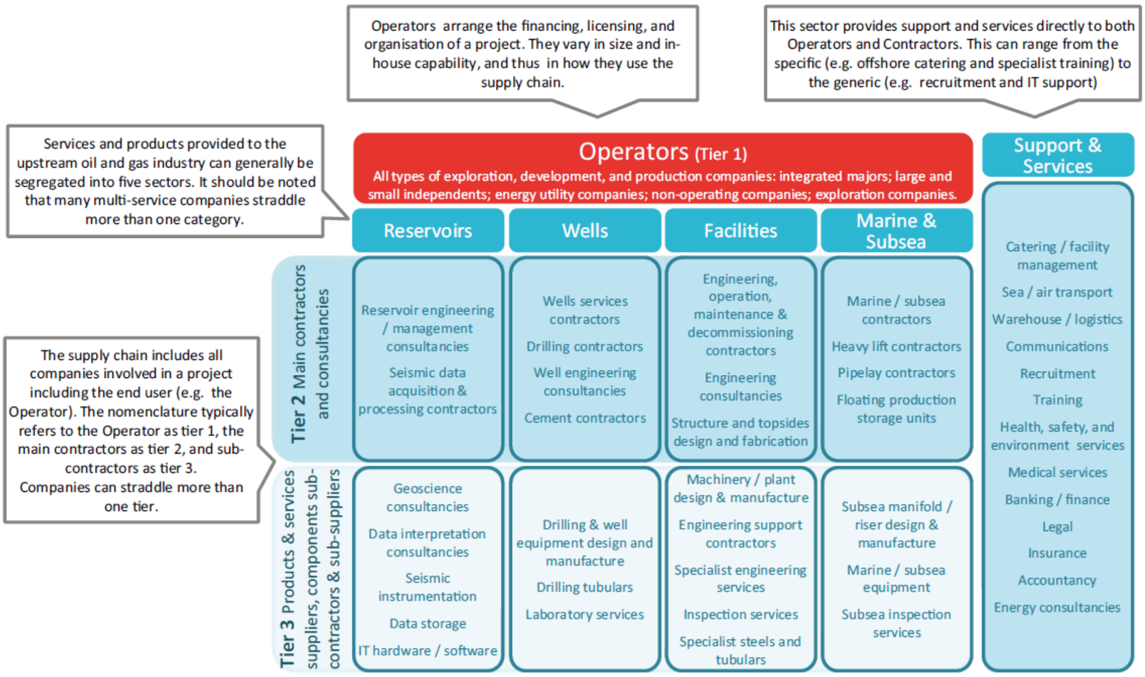
To understand this complex web of activities, there are different ways to categorize. Figure 4.2 explores the range of different specializations and activities. At the top, there are different ranges of operators directly involved in exploration, development and production activities (red box). They are tier 1 players involved in licensing, financing and organizing an upstream project. They outsource some value chain activities to supply and service companies. The services and products provided to first tier operators could be divided into five main categories (Oil and Gas UK Economic Report, 2011):

- **reservoirs,** covering mostly geological activities such as seismic, data acquisition and processing, reservoir engineering and management;
- **wells,** covering drilling, well completions and other related services such as cementing;
- **facilities** covering design, procurement, engineering and fabrication, operation, maintenance, decommissioning and related consultancies;
- **marine and sub-sea** encompassing marine/sub-sea engineering, construction and operations, pipe laying, diving and marine logistics;
- **general support and services** to both operators and main contractors, ranging from direct support such as asset management, catering and logistics to health, safety and environmental services, IT, venture capital, corporate finance, accounting, banking, legal and insurance services.

Tier 3 supply and service companies are sub-contractors of second tier contractors which usually manufacture equipment and provide specialized services. These categories do not necessarily define the firms' boundaries. Upstream business is formed of systems of companies each occupying certain parts of the value chain. They cooperate and compete to bring oil and gas to the marketplace. However, their *'roles'* may change and evolve, and the *'rules'* governing them also vary from time to time.

Technological innovation can play a major role in shifting the boundaries and bring new players to the value chain. These dynamics are discussed in the next section.

Figure 4-2 Upstream petroleum industry value chain[17]



Source: Oil and Gas UK Economic report (2011)

http://www.oilandgasuk.co.uk/economic_report.cfm accessed on 18th Jan 2012

4.5. Dynamics of Industry Architecture

The historical division of labour encompassed oil entrepreneurs, prospectors (experienced geologists), drillers, roughnecks (skilled labour) and roustabout (semi-skilled labour). The main defining lines of the industry have remained similar, distinguishing two main types of companies, i.e. oil operators and service and supply companies. While operators compete in markets for crude oil and gas, service and

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[17] The oil and gas UK economic report prefers the term ‘*supply chain*’ to illustrate the chain of activities from the perspective operators. Some authors also use the term ‘value chain’ to refer to the activities within firms while the term ‘*value system*’ is suggested for the network of activities connecting different firms (for example Porter, 1991). Since there is no standardized way of using these terms, I chose the term value chain to refer to the whole range of activities (functional approach) in upstream industry, simply because it seems more popular and sensible.

supply companies compete in the market for equipment and services required in upstream projects (Acha, 2002).

To understand the industry, it is necessary to recognize the varieties of both operator and service companies. National Oil Companies (NICs) and private International Oil Companies (IOCs also known as majors) are the two types of operators, most of them also cover[18] midstream, downstream and even petrochemicals. Table 4.1 lists Petroleum Intelligence Weekly (PIW) rank of world's top 50 Oil Companies in 2008, comparing NOCs and IOCs based on six operational criteria such as reserves, production, and market capital.

While IOCs mostly emphasise business and financial objectives, NOCs usually follow wider goals combining national, social, political and economic interests. In addition, independent companies are also becoming important players, focusing only on upstream operations. These operators are usually active in small or mature oil deposits, which are not attractive enough for big companies and do not need advanced technology.

There are a diverse range of supply and service companies in the upstream sector, competing in different segments. Table 4.2 lists the top 50 supply and service companies differentiated by their segments and ranked according to their market capitalization. In one perceptive, two main types of supply and service companies are observable. Integrated service companies provide a different range of services. They tend to provide integrated and total solutions. Drilling rig operations, EPC (Engineering, Procurement, and Construction) projects and full packages of logging and data services are examples of their activities (Acha, 2002). In contrast, there are specialized companies with a narrower range of activities in particular segments. Onshore or offshore drillers, equipment producers, seismic services and transportation companies are examples of these more specialized companies.

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[18] In this case they are known as vertically integrated oil companies

Table 4-1 Petroleum Intelligence Weekly Ranks (2008)

PIW's Top 50: How The Firms Stack Up			
2008	**Company**	**Country**	**State Ownership**
1	Saudi Aramco	Saudi Arabia	100
2	NIOC	Iran	100
3	Exxon Mobil	US	
4	PDV	Venezuela	100
5	CNPC	China	100
6	BP	UK	
7	Royal Dutch Shell	UK/Netherlands	
8	ConocoPhillips	US	
9	Chevron	US	
9	Total	France	
11	Pemex	Mexico	100
12	KPC	Kuwait	100
13	Sonatrach	Algeria	100
14	Gazprom	Russia	50.0023
15	Petrobras	Brazil	32.2
16	Rosneft	Russia	75.16
17	Lukoil	Russia	
18	Petronas	Malaysia	100
19	Adnoc	UAE	100
20	Eni	Italy	30
21	NNPC	Nigeria	100
22	QP	Qatar	100
23	INOC†	Iraq	100
24	Libya NOC	Libya	100
25	Sinopec	China	75.84
26	EGPC	Egypt	100
27	StatoilHydro	Norway	65
28	Repsol YPF	Spain	
29	Surgutneftegas	Russia	
30	Pertamina	Indonesia	100
31	ONGC	India	74.14
32	Marathon	US	
33	PDO	Oman	60
34	EnCana	Canada	
35	Uzbekneftegas	Uzbekistan	100
36	Socar	Azerbaijan	100
37	TNK-BP‡	Russia	
38	Apache	US	
38	CNR	Canada	
40	SPC	Syria	100
41	Kazmunaigas	Kazakhstan	100
42	Devon Energy	US	
42	Hess	US	
44	Anadarko	US	
44	Occidental	US	
44	OMV	Austria	31.5
47	BG	UK	
48	CNOOC	China	66.41
49	Novatek	Russia	
50	Ecopetrol	Colombia	89.9

Source: http://www.energyintel.com/documentdetail.asp?document_id=648479

Table 4-2 Top 50 Oil and Gas Service Companies

Rank Market Capitalization	Company	Industry Segment	Market Capitalization, $ Million
1	Schlumberger Ltd.	International Integrated	39,775
2	Halliburton Company	International Integrated	17,244
3	Baker Hughes Inc.	International Integrated	9,367
4	Transocean Sedco Forex	Offshore Drillers	9,330
5	Weatherford International	Oilfield Equipment	6,065
6	Nabors Industries	Onshore Drilling	5,271
7	Diamond Offshore Drilling Company	Offshore Drillers	4,963
8	Noble Drilling Corporation	Offshore Drillers	4,823
9	ENSCO International	Offshore Drillers	4,119
10	BJ Services Company	Oilfield Equipment	4,534
11	Global Marine, Inc.	Offshore Drillers	3,730
12	Smith International	Oilfield Equipment	3,625
13	R&B Falcon Corp.	Offshore Drillers	3,582
14	Santa Fe International	Offshore Drillers	3,443
15	Cooper Cameron Corporation	Oilfield Equipment	3,419
16	Rowan Companies	Offshore Drillers	2,466
17	National Oilwell	Oilfield Equipment	1,810
18	Helmerich & Payne	Onshore Drilling	1,643
19	Tidewater Inc.	Transportation	1,579
20	Colflexip Stena Offshore	Diving/Construction	1,521
21	Hanover Company	Oilfield Equipment	1,481
22	Petroleum Geo-Services	Seismic Services	1,354
23	Marine Drilling Company	Offshore Drillers	1,300
24	Pride International	Offshore Drillers	1,293
25	Lone Star Technologies	Oilfield Equipment	1,156
26	Global Industries	Diving/Construction	1,080
27	Atwood Oceanics, Inc.	Offshore Drillers	828
28	Key Energy Services	Onshore Drilling	791
29	Patterson Energy Inc. .	Onshore Drilling	787
30	Cal Dive International	Diving/Construction	715
31	Varco International	Oilfield Equipment	711
32	Seacor SMIT	Transportation	665
33	Tuboscope Inc.	Oilfield Equipment	650
34	UTI Energy	Onshore Drilling	572
35	Grey Wolf	Onshore Drilling	558
36	Veritas DSG	Seismic Services	554
37	Carbo Ceramics	Oilfield Equipment	471
38	Maverick Tube Corp.	Oilfield Equipment	469
39	McDermott International	Diving/Construction	460
40	Oceaneering International	Diving/Construction	375
41	Unit Corporation	Onshore Drilling	356
42	Input/Output Inc.	Seismic Services	311
43	Parker Drilling Company	Onshore Drilling	310
44	Stolt Comex Seaway	Diving/Construction	285
45	Offshore Logistics	Transportation	269
46	Friede & Goldman	Oilfield Equipment	269
47	Trico Marine	Transportation	198
48	TETRA Technologies	Oilfield Equipment	169
49	Seitel Inc.	Seismic Services	158
50	Gulfmark Offshore	Transportation	151
51	Gulf Island Fabrication	Diving/Construction	148

Source: http://www.petrostrategies.org/Links/service_companies.htm

Operators have continuously shown some kind of cartelistic behavior. The ‘seven sisters’ were dominant by 1980s controlling about eighty five percent of world petroleum deposits. The wave of nationalization in producing countries led to the emergence of a new ‘seven sisters[19]’. They are predominantly state-owned companies. They controlled about one third of oil and gas production and more than one third of world reserves in 2005. In contrast, the share of old ‘sevens sisters’ group – are now merged into four companies- reduced to about 10 percent of oil and gas production and 3 percent of world reserves (Hoyos, 2007).

The new ‘seven sisters’ are not however homogenous, with a high level of coordination. In addition, their managerial, organizational and technological capabilities are still far behind what the IOCs accumulated over time. They follow different motives, interests and strategies. Figure 4.3 is a heuristic illustration of the variety of NOCs, positioning them alongside two dimensions - technological competence and production status. Some of them are national asset holders, others market, technology, finance or strategic resource seekers. While some of them are losing production levels and their technical capacities have been challenged, some of them like Petrobras and Petronas have caught up technologically with many IOCs. It might not even be accurate to call some of them NOCs anymore; as they are listed in international financial markets and their operations are dispersed globally.

Historically, IOCs became vertically integrated - upstream, midstream and downstream - to be able to manage the impacts of oil price volatility and avoid supply interruption for downstream activities (Penrose, 1971; cited in Acha, 2002). Therefore, there was no technical reason to integrate upstream to downstream, but economic and political factors forced backward vertical integration (Weston et al., 1999). Chandler (1990) provides examples of American oil companies to support his theory of vertical integration and formation of multidivisional firms. In his view the ‘visible hand’ of big companies seemed more efficient to cope with market expansion and cost reductions after World War II (Acha, 2002).

In addition, horizontal integration in the form of mergers and acquisitions (M&A) has been one important feature of the upstream industry. One important wave of M&As

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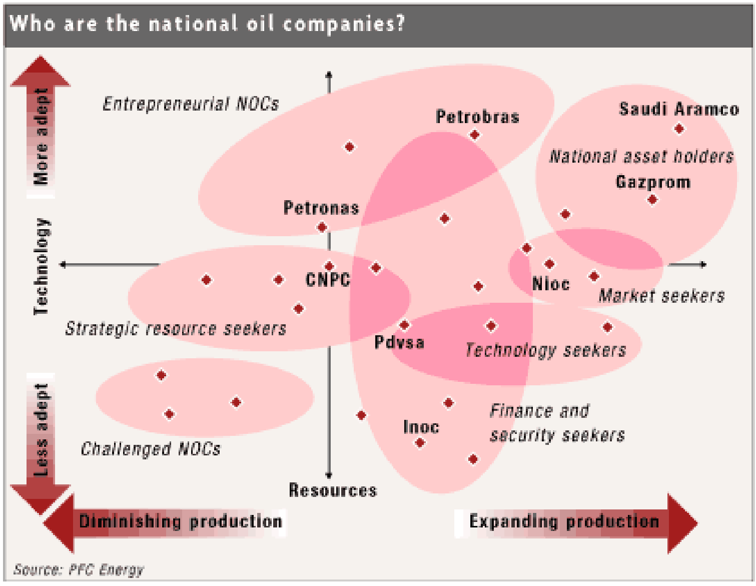
[19] They include Saudi Aramco, Russia’s Gazprom, CNPC of China, NIOC of Iran, Venezuela’s PDVSA, Brazil’s Petrobras and Petronas of Malaysia

among majors occurred in the early and mid-1980s to regain their position after nationalization of their assets in producing countries. Weston et al., (1999) adds that M&A in that period was not particular to oil industry. Global forces such as technical change, globalization, privatization and instability pushed many other industries to consolidate.

Figure 4-3 The relative position of the new 'seven sisters'



Source: Hoyos (2007).

Collapse of oil prices in mid 1980s was a major driver for industry restructuring and emergence of a new industry architecture. As a result of sustained low oil prices, oil majors implemented cost reduction programs to increase their efficiency. Fluctuations around the average low prices drove them to change their cost structure from fixed to variable. They chose to lease many types of equipment from service companies previously owned by them. The aim was to increase flexibility and responsiveness to change (Weston et al., 1999). This created a massive opportunity for supply and service companies to takeover some parts of the activities previously done by operators. Technological progress in the industry and the need for specialization was probably another driver.

These forces altered the division of labour between operators and supply and service companies. Oil operators reevaluated their activities to explore their real competitive domain and redefine their core and non-core areas. Their new strategy was to focus on their competitive advantage. Exploration of productive reserves and efficient management of these assets over their long life cycle became the major competitive domain of operators. The provision of equipment and services in different phases of exploration, development and production of reserves became the responsibility of supply and service companies (Acha, 2002).

The 1986 counter shock was a key turning point for oil service companies, pushing them towards horizontal and vertical integration strategies (Babusiaux et al., 2004). Similar to operators, service companies also restructured themselves in order to increase efficiency, faced with a declining market in the second half of 1980s. They redefined their portfolios, focusing on what they considered their main expertise, selling less relevant units. An external growth strategy was also undertaken by smaller specialized service companies in drilling and geophysical services (Barreau, 2002). The result was the relative expansion of specialized supply and service companies in the sector.

Some major supply and service companies gradually began to provide a broad range of services to their clients to meet their expanding needs for bigger and more complex exploration and development projects. ‘Total solution’ or ‘integrated solution’ gained momentum as a customer relationship strategy when operators requested more packaged services instead of discrete activities. This increasing demand for integrated services pushed big supply and service companies to build project management and integration capabilities, which was previously the territory of operators.

Alteration of industry architecture and technological advancement resulted in productivity improvement and cost reduction in the industry. From the mid-1980s to mid-1990s, the average cost of finding and lifting oil fell considerably. This happened in spite of the upward trend expected, stemming from the aging of existing fields and decline in easy access deposits (Fagan, 1997). Nonetheless, there was a ceiling for this downward trend and began to rise in the mid-1990s. Continued declining oil prices concurrent with natural rise of exploration and development costs got oil majors into trouble. Stock markets responded to low rate of returns. Funding new projects became difficult in the environment of volatile and declining income trends. The result was the rise of mega mergers in late 1990s and early 2000s to reduce the costs and risks of the industry and mobilize resources.[20].

In spite of these consolidations, IOCs underperformed financially in most of the last decade compared to NOCs and service companies (Benayoun, and Whittaker, 2009). This reflects the limited growth opportunities for IOCs under their current business model, as they are not able to replace depleted reserves while most NOCs control their national reserves. In addition, the IOCs' historical differentiating expertise – such as technological capabilities, financing capabilities, and system integration and project management capabilities - has been challenged. Less investment in technology and outsourcing of many technical and engineering parts to service companies transformed the role of IOCs. They changed from project executor with in-house capabilities to become a project orchestrator and system integrator relying on a network supply and service companies (Benayoun, and Whittaker, 2009).

In fact, this third stage of evolution evolved from the second phase, triggered by a search for a fuller degree of integration and exploitation of interactions and synergies between different activities. Near the turn of the century from 1998 to 2001, service and supply industry experienced mega mergers in which very big companies expanded their size while at the same time refocused their activities. These changes under continuous low oil prices had distinguishing features. First, the scale of acquired assets was much larger. Second, the scope of integration encompassed several service segments for major service companies. The overall result was an unprecedented record of industry consolidation, similar to what happened to major operators in the same period (Barreau, 2002).

These architectural adjustments created a very concentrated service sector. According to Babusiaux et al. (2004), three service majors accounted for more than 70% of total oil and gas service market at the end of the century. The share of these giant companies reached over 90% in directional drilling and logging, the segments which are highly knowledge intensive. In 2009, the top four companies in the exploration and evaluation

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[20] The list of merges is as follows: BP/Amoco/Arco; Total/Elf/Petrofina; Exxon/Mobile; Chevron/Texaco

services market accounted for about 80% percent of market share (GBI Research, 2010).

The behavior of the sector over the last decade seems puzzling at first glance, compared with the 1980s period. Prolonged low oil prices after 1986 began to reverse in 2002, expressing a sharp rising trend. Nonetheless, M&A activities have continued with an even stronger pace particularly since 2006 (Davies, 2007). While low oil prices in late 1980s triggered waves of M&A to enable service companies to survive, M&A activities continued in the high oil price environment of 2000s when the service sector is performing well. This M&A trend is still ongoing and industry analysts expect much more to come (Pfeifer, 2011; Lazarov, 2011). This suggests that consolidations in both periods do not necessarily follow the same logic and must be explained according to different mechanisms.

Directly related to oil prices, demand for petroleum supply and services has been different among these two periods. A shrinking market and low demand triggered consolidations in the late 1980s and 1990s. In the post 2002 period "increasing demand and high crude prices are underpinning merger and acquisition activity" (Pfeifer, 2011). It is clear that downturn in the service market pushes consolidation, because it creates economy of scale and scope and higher returns for shareholders. We may call it 'market led' mechanism for consolidation operating under declining and low profit markets.

Clearly, the same argument cannot be applied to post 2002 period as prices are high and the service market is growing fast. Experts' opinion on drivers of recent consolidations in service sector could be informative. The Director of Energy at McGladrey Capital Markets and an expert in M&A activities, explained recent M&A activities as follows:

> "Due to the service-intensive nature of unconventional wells, *large integrated service providers* are best suited for this type [i.e.unconventional] of drilling. These service-intensive development and exploration areas require the broad-based product and service offerings and global footprint that the *large integrated vendors* can provide. ... *Another catalyst for OFS acquisitions is technology* as major players continue to look for companies that can deliver the innovative drilling technology required in areas such as shale extraction. The industry's shift toward horizontal drilling and advanced completion/stimulation techniques has been a seminal event for OFS vendors, transforming what had been a relatively sleepy, mature sector into a hotbed of activity and technological innovation." (Lazarov, 2011)[Emphasis added]

Another example is the view of Chad Deaton; Bake Hughes' CEO on acquisition of BJ services:

> "will better position us to drive international growth and to compete for the growing large integrated projects by incorporating pressure pumping into our product offering," (Baker Hughes, 2009).

He also emphasises that companies should be large enough to afford the high R&D costs required for increasingly large complex projects.

It is clear from these quotes that change in the nature and 'quality' of demand (e.g. service-intensive nature of unconventional wells or size and complexity of the projects) and its technological imperatives play a key role in the recent M&A activities. We may call this post 2002 consolidation more 'technology led', because it is a route for access to, and integration of different advanced technologies enabling companies to operate in complex upstream projects.

Compared with '*market led'* consolidations in 1980s and 1990s, *'technology led'* drivers seem dominant in post 2000 M&A discourse. Meeting these technological requirements involves high R&D costs which are not affordable by small companies. This new environment in upstream petroleum industry is more favourable to big vertically integrated companies with patterns of innovation which is closer to Schumpeter Mark II. We examine this hypothesis regarding the change in sectoral pattern of innovation in the chapter 6.

In sum, dynamics of industry architecture express three different phases since 1970. The first phase is the period of oil shocks when operators have a dominant role. The second phase is the period of collapse of oil prices. This triggered M&A activities among majors and service companies, and at the same time accelerated outsourcing strategies. The result was the relative expansion of specialized supply and service companies. The third phase is the period of gradual vertical integration of major service companies. This enabled them to cope with the increasing demand for total and integrated solutions that operators called for. We addressed the dynamics of industry architecture or *sectoral production system* of upstream petroleum industry in this section. The next section discusses the nature and dynamics of *sectoral innovation system*.

4.6. Sectoral innovation system

The aim of this section is to explore the role of technological innovation in the evolution and dynamics of this industry using the SIS framework and identify the main actors involved. As explained in chapter 3, the advantage of this framework is its systemic, integrated and dynamic approach and its focus on the knowledge base of the specific sectors. First, I review critically (in section 4.6.1) the theoretical frameworks concerning drivers of innovation in the upstream sector. It is shown that a simple linear supply/demand analysis provides a partial picture of the industrial dynamics of the sector. Next, in section 4.6.2, I provide an updated trend of innovative activities in upstream petroleum industry to examine and refine the suggested theoretical frameworks. It is shown that dynamics and transformations of the sector could be understood more comprehensively within SIS/IA frameworks. In addition I provide a description of the nature of the knowledge base in section 4.6.3 and of the main innovators in the sector in the section 4.6.4. This section provides a background for further analysis of the dynamics of knowledge base complexity in the next chapter.

4.6.1. Drivers of innovation

According to Isabelle (2001), incentives for innovation in the upstream petroleum industry remained very weak for about fifty years from the 1920s when it was internationalized. However from 1970s onward, technical challenges in the industry made innovation much harder. This was reinforced by the oil counter shock of the middle 1980s which induced fierce competition. She labels the first period as *'technological tranquillity'* and the second one as *'technological revolution'*. According to her view, international oil companies were largely relying on exogenously given technologies in the first period, while they subsequently became active creators of new technologies.

Her theory of innovation recognizes two driving factors, technical demands operated from the 1970s, reinforced by competition pressures induced by low oil prices after 1986. From the technical point of view, industry was experiencing long-term diminishing marginal cost from 1920-1970s, relying on easy access to increasingly giant reserves. Reserves were found largely in the Middle East and in other parts of the world where international oil companies could operate. The formation of the seven sisters in 1928 created an oligopolistic structure where competitive forces for innovation remained weak.

From the early 1970s the situation changed dramatically. Nationalization of the petroleum industry in many countries lowered easy access to cheap oil, and big reservoirs became unsecure and limited. There was no alternative but to seek oil in remote harsh areas like Alaska and the North Sea which required new sophisticated technologies. This technical demand was amplified by competitive pressures driven by low oil prices after 1986. From this perspective, oil prices have had a negative and indirect effect on innovation channelled through competitive pressures.

Thurston and Stewart (2005) suggest a more comprehensive theory adding a supply-side technology push aspect to Isabelle's (2001) demand-pull theory. The empirical analysis of Thurston and Stewart (2005) concludes that major shifts in supply of externally created technology and the expected demand for new techniques during high oil prices drove innovation in the petroleum industry. Their empirical evidence, however, has some inconsistencies with Isabelle's (2001) framework.

The first inconsistency is the '*technological tranquillity*' period before the 1970s. The collected evidence shows that both demand and supply side forces have driven innovation in the sector, even before 1970s. Second, the historical data do not support the Isabelle idea that the competitive environment induced by low oil prices after 1986 has driven innovation. The reason seems to be lack of enough financial resources for R&D investment, even if competitive pressures increased, as Isabelle (2001) claims. The typical behaviour of companies in weak market conditions is production at marginal costs where little profit is left to be spent in very risky activities like innovation. In addition, high exploitation cost reservoirs are not economically viable in low price conditions. Therefore demand for new advanced technology is weak. We already know that the first response of both operators and service companies to low oil prices was cost reduction and restructuring programs and less R&D expenditure, as discussed in section 4.5.

The theoretical framework of Thurston and Stewart (2005) predicts a proliferating landscape for the future of innovation in oil and gas. This is due to the coincidence of both strong demand forces stemming from increasing exploration and development (E&D) expenditures, and external technology diffusion into the upstream petroleum industry from other new industries. In the next section, we see how a systemic perspective completes this picture and sheds light on innovation dynamics.

4.6.2. The dynamics of innovation in SIS perspective

In this section, we take a systemic view to explain the dynamics of innovation. We found that simple correlation analysis of supply and demand factors is not sufficient to explain these dynamics. In contrast, the SIS approach equipped with a systemic and evolutionary perspective not only considers the supply and demand factors, but also how they interact with industry architecture in different phases. The combination of these factors shapes the rate of innovation in different periods. The trend of oil prices presented in figure 4.1 is considered as both supply and demand factor. It pushes innovation through higher R&D investments. It also pulls innovation through stimulation of demand for new techniques, because it makes more complex and expensive deposits economically viable.

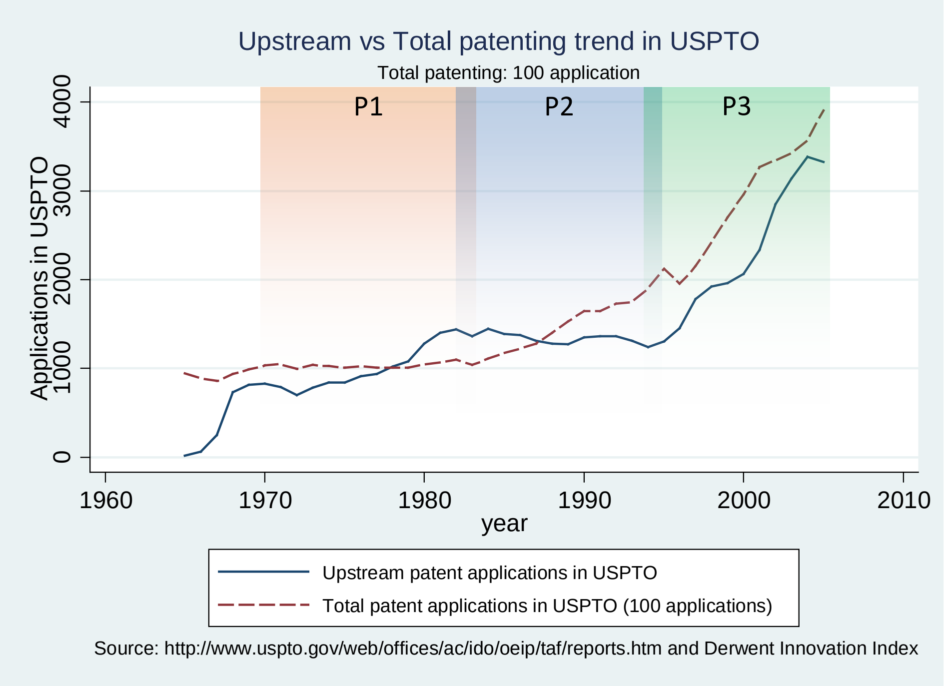
Figure 4.4 presents the innovation trend in the upstream petroleum industry according to the number of patent applications in the US patent office (solid line). The dash-line shows the trend of total patenting in USPTO at 1% scale to control for technology push factor. In other words, we could understand the extent to which observed dynamics of innovation in upstream sector is a reflection of technology push from other sectors, or the result of internal mechanisms within the sector.

According to figure 4.4, 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 almost doubled from about 700 per year in 1970 to about 1450 in 1984. The second period runs from 1984 to 1994, with a negative trend in innovation. Third period begins after 1994 when industry grows and looks very innovative.

The first period corresponds to the first and second oil shock periods when oil prices were very high and worries of oil scarcity dominant. These two factors provided both powerful motives for upstream R&D investment. The aim was to open up more challenging reservoirs in harsh locations and the key was technology. These technological efforts were enormously successful to bring down exploration and production (E&P) costs and increasing reserve replacement ratios. The stable trend of total patenting in this period suggests that the rise of innovation is not attributable to this trend and should be explained according to other factors.

Combined with other geopolitical factors, explained in section 4.2, this technological progress consequently led to excessive supply, pushing down oil prices for more than one and half decades. This self-correcting mechanism brought the upstream industry into the second period when patenting took a negative trend from the mid-1980s to the mid-1990s. This negative feedback loop could be seen as a long term and indirect impact of oil prices on innovation in the sector.

Figure 4-4 The number of US patent applications over time



Source: http://www.uspto.gov/web/offices/ac/ido/oeip/taf/reports.htm and Derwent Innovation Index

According to Hotelling’s law (Babusiaux et al.; 2004, pp.45) oil price is a function of its scarcity. Scarcity is also subject to change according to available technology. Therefore, oil prices seemed to have negative impacts on innovation in the long term, although it drove innovation in the short term. This is because availability of better technology provided by R&D investments in the first period reduced the level of scarcity. In other words, technical progress enhanced access to more and cheaper resources which led to oversupply of crude oil and other fossil fuels. In the longer term, it decreased oil prices and weakened demand side forces for innovation.

In addition to interacting supply and demand forces, it is argued that firm size and industry structure is an important determinant of innovation. In an empirical analysis of the US oil industry in the 1970s, Teece and Armour (1976) showed that industry divestiture has a harmful impact on innovation in the sector, particularly with regard to big high-risk and long-term R&D programs. The main explanation is that minimum scale economy will be lost in smaller companies. In addition, vertical disintegration prevents synergies between different parts of the value chain and may block interactions between research activities and applications. The argument favours more a concentrated and oligopolistic structure for technological leadership, contrary to Isabelle's (2001) competition argument.

The second period shows about a 15% decline in upstream innovation while total patent application moves in the opposite direction expressing more than 70% growth over that period. This suggests that low oil prices have been an important disincentive for innovation, although total patenting has been growing fast. In other words, availability of technological opportunities from other industries is not very effective when demand for innovation is week. As seen from the last section, organizational innovations such as rationalization, reorganization and M&A activities might be more appropriate and less risky strategies. This rejects Isabelle's (2001) proposition that low oil prices stimulated innovation, because of a more competitive environment.

The third period is more complicated to analyze. While there is no large change in oil prices until 2002, nor technology-push trend (dash line in the figure 4.4) compared to second period, the innovation performance of the industry has dramatically increased. The number of patent applications for upstream petroleum industry grew from about 1250 in 1994 to 3350 in 2005 experiencing about 170% growth. In fact, this period could be labelled as a real *'technological revolution'* or even '*technological explosion*'. The key question is what factors are responsible for this radical shift? What is striking is that oil prices stayed low for most of this period. In spite of low oil prices, the innovation trend in upstream petroleum took a sharp onward trend after 1994, at least 6 year before rising oil prices.

Several possible complementary explanations could be suggested for this innovation jump. At first glance technology push theory could help. As is evident from figure 4.4, total patent applications increased from about 19,000 in 1994 to more than 39,000 in 2005 showing almost 105% growth, meaning 35% more than its growth rate in the second period. Although this seems acceptable as part of the answer, it is not sufficient for explaining the very radical shift in upstream innovation. The minus 15% growth rate in second period increased to about 170% over the third period, a185% increase in growth rate. Ceteris paribus, we expect a 35% increase in innovation growth as the function of technology push mechanism. The rest of the gap between should be explained by other factors.

According to the historical context, the explanation could be completed by the combination of demand side and industry architecture. There is supporting evidence, as explained in sections 4.5 and 4.6.1, that emergence of ‘qualitatively’ very different and powerful demand for innovation is partly responsible for the recent technological revolution of the industry. The cost of finding and lifting oil which had a downward trend for about 15 years began to rise since 1995 (U.S. EIA, 2011). This is a sign of approaching end of easy oil. The nature of services, equipment, design and engineering in upstream projects should be adapted to geological location and geophysical characteristics of the reservoir such as the shape, size, temperature, and type of rocks. As time goes by, easy oil both in terms of the location and other characteristics is depleted and companies look for more difficult less-accessible locations and more challenging types of material to extract. Advanced and complex technology became a matter of survival, not just a tool for higher profits.

Nonetheless, available industry architecture, formed mostly of operators and specialized service companies, was not very efficient to cope with new technological imperatives of the sector. Given low oil prices and limited resources for innovation, more efficient industry architecture is required to increase the productivity of the innovation system.

The emergence of new large integrated service companies could be seen as a key factor in the rise of productivity in the innovation system. Larger scale M&A activities moved the sector to a more concentrated industry structure which for Teece and Armour (1976) is more favourable for innovation. This systemic analysis suggests that reconfiguration of industry architecture was an organizational industry-wide response to the new technological requirements. This industry restructuring enabled the sector to express a surge in innovation trend, in spite of continued low oil prices. This analysis suggests that a systemic and dynamic approach is helpful to explain the dynamics of innovation and sheds light on transformations of sectoral innovation systems. In addition to supply and demand related factors, SIS approach considers their dynamic interactions with industry architecture over time.

Although petroleum industry is not usually recognized as an innovation and patent intensive sector, this traditional measure of innovative activity confirms that flow of innovation has experienced a ‘technological explosion’ since 1995. This picture is not compatible with the standard version of industry life cycle theory (Utterback and Abernathy, 1975) which assumes that mature industries usually become exhausted of innovation. Our patent database does not cover the period after 2005. Yet, we expect that such acceleration in innovation trends has continued as a result of marriage of high oil prices, depletion of easily accessible reserves, increasing share of unconventional reserves, and diffusion of general purpose technologies from other industries into the upstream sector. All in all, the service intensity of E&P activities and their knowledge content have been incredibly increased over time, such that Surya Rajan from IHS Cambridge Energy Research Associates says:

> “If all technological innovations produced by the oil and gas industry were added up, they would probably rival NASA’s space program or the Industrial Revolution.” (Rajan, 2011. p. 11)

4.6.3. Knowledge and technologies

One of the fundamental building blocks of SIS is the knowledge base which feeds the innovation process in the sector. Accordingly, the boundaries of each sector may change from time to time as the knowledge base of the sector evolves and working technologies change. Patent data is a very informative and detailed source to trace domains of knowledge contributing to different sectors. I present here some analysis of the main knowledge domains in upstream petroleum based on both the International (IPC) and Derwent patent classification systems. According to the nature of these classifications, IPC could illustrate the knowledge domains mostly in terms of their scientific and technical discipline. Derwent on the other hand could shed light more on their industrial application (Acha and Brusoni, 2005). Nonetheless, they are not always clear cut and these classification schemes may overlap.

Table 4.3 summarises the numbers and shares of patents in each IPC section at the 1-digit IPC level. It shows that all 8 main IPC sections contribute to the knowledge base of the industry, though their shares greatly vary from about 40% at the top for fixed constructions (E) to about 0.4% at the bottom of table for textile and papers (D). Table 4.4 provides similar information at more disaggregation levels, showing very unequal distribution in classes and sub classes. Sometimes, the main technological domains are identified easier by looking at disaggregated data, because aggregated groups refer to functions rather than technological disciplines.

Table 4-3 Knowledge domains of upstream petroleum: 1 digit IPC

Rank	One digit IPC class (Section)	Freq.	Percent	Cum.
1	**E**:FIXED CONSTRUCTIONS	26,000	39.21	39.2
2	**C**:CHEMISTRY; METALLURGY	13,101	19.76	59
3	**B**:PERFORMING OPERATIONS; TRANSPORTING	8,988	13.55	72.5
4	**G**: PHYSICS	8,245	12.43	85
5	**F**:MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING	6,978	10.52	95.5
6	**H**:ELECTRICITY	1,707	2.57	98.1
7	**A**:HUMAN NECESSITIES	1,037	1.56	99.6
8	**D**:TEXTILES; PAPER	253	0.38	100
Total		66309	100	100

As tables show, in the section fixed constructions (E), drilling technologies and a variety of related techniques to survey, test, or complete the oil wells are included. In addition, hydraulic engineering for subsea constructions is a major area. Chemistry is the second largest contributing section which covers near 20% of inventions. It includes a different range of chemical processes such as organic and inorganic compounds, and solutions to environmental challenges.

Table 4-4 Knowledge domains of upstream petroleum: technological areas based on 3, 4, or 7 digit IPC classes

Main Section	3, 4 or 6 dig high number subclasses		Percent
E	E21B-043	Methods or apparatus for obtaining oil, gas, water, soluble or meltable materials or a slurry of minerals from wells	7.81
	E21B-033	Sealing or packing boreholes or wells	4.46
	E21B-047	Survey of boreholes or wells	3.35
	E21B-017	Drilling rods or pipes; Flexible drill strings; Kellies; Drill collars; Sucker rods; Casings; Tubings	2.75
	E21B-007	Special methods or apparatus for drilling	2.21
	E21B-023	Apparatus for displacing, setting, locking, releasing or removing tools, packers or the like in boreholes or wells	2.13
	E21B-021	Methods or apparatus for flushing boreholes, e.g. by use of exhaust air from motor	1.61
	E21B-019	Handling rods, casings, tubes or the like outside the borehole, e.g. in the derrick; Apparatus for feeding the rods or cables	1.59
	E21B-034	Valve arrangements for boreholes or wells	1.58
	E21B-010	Drill bits	1.51
	E21B-049	Testing the nature of borehole walls; Formation testing; Methods or apparatus for obtaining samples of soil or well fluids, specially adapted to earth drilling or wells	1.51
	E02	HYDRAULIC ENGINEERING; FOUNDATIONS; SOIL-SHIFTING	2.47
C	C09	DYES; PAINTS; POLISHES; NATURAL RESINS; ADHESIVES;	5.77
	C10	PETROLEUM, GAS OR COKE INDUSTRIES; TECHNICAL GASES CONTAINING CARBON MONOXIDE; FUELS; LUBRICANTS; PEAT	2.99
	C08	ORGANIC MACROMOLECULAR COMPOUNDS; THEIR PREPARATION OR CHEMICAL WORKING-UP; COMPOSITIONS BASED THEREON	2.85
	C07	ORGANIC CHEMISTRY	1.76
	C04	CEMENTS; CONCRETE; ARTIFICIAL STONE; CERAMICS; REFRACTORIES	1.29
	C02	TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE	1.24
	C01	INORGANIC CHEMISTRY	0.9
B	B63	SHIPS OR OTHER WATERBORNE VESSELS; RELATED EQUIPMENT	2.16
	B23	MACHINE TOOLS; METAL-WORKING NOT OTHERWISE PROVIDED FOR	1.04
	B65	CONVEYING; PACKING; STORING; HANDLING THIN OR FILAMENTARY MATERIAL	0.59
G	G01V	GEOPHYSICS; GRAVITATIONAL MEASUREMENTS; DETECTING MASSES OR OBJECTS	5.84
	G01N	INVESTIGATING OR ANALYSING MATERIALS BY DETERMINING THEIR CHEMICAL OR PHYSICAL PROPERTIES	2.16
	G06F	ELECTRIC DIGITAL DATA PROCESSING	1.08
F	F16	ENGINEERING ELEMENTS OR UNITS; GENERAL MEASURES FOR PRODUCING AND MAINTAINING EFFECTIVE FUNCTIONING OF MACHINES OR INSTALLATIONS; THERMAL INSULATION IN GENERAL	5.58
	F04	POSITIVE-DISPLACEMENT MACHINES FOR LIQUIDS; PUMPS FOR LIQUIDS OR ELASTIC FLUIDS	1.49
	F25	REFRIGERATION OR COOLING; COMBINED HEATING AND REFRIGERATION SYSTEMS; HEAT PUMP SYSTEMS; MANUFACTURE OR STORAGE OF ICE; LIQUEFACTION OR SOLIDIFICATION OF GASES	0.6
	F17	STORING OR DISTRIBUTING GASES OR LIQUIDS	0.54
H	H01	BASIC ELECTRIC ELEMENTS	0.97
	H04	ELECTRIC COMMUNICATION TECHNIQUE	0.81
A	A61	MEDICAL OR VETERINARY SCIENCE; HYGIENE	0.6
	A01	AGRICULTURE; FORESTRY; ANIMAL HUSBANDRY; HUNTING; TRAPPING; FISHING	0.49
D	D21	PAPER-MAKING; PRODUCTION OF CELLULOSE	0.14

Table 4-5 Knowledge domains of upstream petroleum: industrial applications based on 1, 3 digit Derwent classification codes

Derwent Section		Percent	Derwent class		Percent
Q	Mechanical	92.89	Q49	Mining	66.12
			Q67	Pipes, joints, fittings	5.62
			Q42	Hydraulic engineering, sewerage	4.71
			Q24	Ships	3.90
			Q56	Pumps	2.36
			Q66	Valves, taps cocks	1.90
A	Polymers and Plastics	28.14	A97	Miscellaneous goods not specified elsewhere	10.83
			A14	Other substituted mono-olefins, PVC, PTFE	3.15
			A88	Mechanical engineering, tools, valves, gears, conveyor belts	2.79
			A25	Polyurethanes, polyethers	1.67
			A93	Roads, building, construction flooring	1.54
			A11	Polysaccharides, natural rubber, other natural polymers	1.44
S	Instrumentation, Measuring and Testing	18.19	S03	Scientific Instrumentation, photometry, calorimetry	14.20
			S02	Engineering Instrumentation, recording equipment, general testing methods	3.72
E	General Chemicals	11.45	E19	Other organic compounds general - unknown structure, mixtures	2.65
			E36	Non-metallic elements, semi-metals (Se, Te, B, Si	1.76
			E17	Other aliphatics	1.61
X	Electric Power Engineering	10.81	X25	Industrial Electric Equipment	9.27
P	General	10.26	P43	Sorting, cleaning, waste disposal	1.37
			P41	Crushing: centrifuging, separating solids	1.20
D	Food, Detergents, Water Treatment and Biotechnology	7.70	D15	Treating water, industrial waste and sewage	2.32
			D21	Preparations for dental or toilet purposes	1.23
J	Chemical Engineering	5.77	J01	Separation including e.g. evaporation, crystallisation etc.	3.61
			J04	Chemical/physical processes and apparatus including catalysis	1.38
T	Computing and Control	4.91	T01	Digital Computers	3.75
W	Communications	4.29	W05	Alarms, Signalling, Telemetry and Telecontrol	2.27
M	Metallurgy	3.45	M14	Other chemical surface treatments	1.20
L	Refractories, Ceramics, Cement and Electro(in)organics	3.41	L02	Refractories, ceramics, cement	3.01
G	Printing, Coating, Photographic	2.70	G02	Inks, paints, polishes	1.60
F	Textiles and Paper-Making	2.38	F09	Paper-making production of cellulose, chemical treatment of wood	1.48
K	Nucleonics, Explosives and Protection	2.05	K08	Nucleonics, X-ray techniques	1.22
V	Electronic Components	1.88			
C	Agricultural Chemicals	1.32			
B	Pharmaceuticals	1.08			
U	Semiconductors and Electronic Circuitry	0.64			

The main category in Section B (about 14%) is allocated to performing operations and transportation. This covers ship engineering and vessels used for offshore operations. Geophysical sciences and electric digital processing to visualize the collected information are main categories in the section G which stands for Physics covering more than 12% of the patents.

Table 4.5 illustrates the main industries in which patents have been co-classified in addition to upstream petroleum (H01). These figures signal the degree of knowledge base overlap between upstream petroleum industry and other sectors. The data is provided in 1-digit and 3-digit levels of aggregation, because of very uneven distribution of patents. The table rank is based on section percentages and within each section according to class percentages.

As may be expected, mining (Q49) is the most similar industry to upstream petroleum in terms of the knowledge base, because more than 66% per cent of patents of upstream have also applications in the mining industry. Within the same section, pipes, hydraulic engineering, shipping, pump and valves are also important. Polymer and plastic industry is the next important industry accounting for about 28% of patents. Scientific and engineering instrumentation industry is in the next position with share of near 18%. The main lesson from this table is the diversity of industries which play a role in one or another segment of the upstream petroleum industry. One implication is that in order to have a strong and developed upstream petroleum industry, a region or country needs a diverse range of other industries. On the other hand, if a country is competitive in these overlapping industries, it can exploit this knowledge in some segments of upstream sector.

4.6.4. Key actors and players

Upstream petroleum is sometimes understood as a kind of passive innovation system in which the main source of innovation is outside the sector. This view is embedded in resource curse theories reviewed in the chapter 1 where resource based industries are not considered as technologically dynamic sectors. In other words, it is assumed that the sphere of innovation is mostly the responsibility of other industries which produce new tools and techniques for oil exploration and production operations. According to this view, the role of oil companies is to guide innovation processes as 'users' by articulating their needs and requirements. At most, they may play the role of 'lead users' (Von Hippel, 1986) providing product concepts and design to facilitate the innovation process by external innovators, or fund R&D activities. In terms of Pavitt's taxonomy (Pavitt, 1984), this would be an example of supplier-dominated sectors such as textile and services where new technologies are embodied in new equipment and capital goods. Learning by doing and using is the dominant form of learning process. Nonetheless, Pavitt and Von Hippel have not explicitly talked about the upstream petroleum industry.

As we will be seen in this section, and also with more elaboration in chapter 6, this is a very simplistic view of the innovation process in this sector. This view might have been accurate in the early developments of the industry, but is no longer valid. Not only are a diverse range of actors within the upstream sector involved actively in the innovation processes, but their roles and patterns of interaction in networks of innovation have changed, along with market and technological dynamics. Analysis of the upstream sector does not support a static and technologically passive picture. In contrast, the systemic and dynamic perspective of SIS approach sheds new light on the active role of internal actors of the sector in innovation processes.

Table 4.6 presents the list of top 50 innovators in upstream petroleum industry ranked based on the number of the patents registered in the Derwent Innovation Index between 1965 and 2009. This table classifies the actors according to their role in the industry, distinguishing between integrated oil companies (IOCs), integrated service companies (ISCs), research and development institutes (R&D) and specialised service and supply companies (SSCs)[21]. The main business segments of the companies are also presented. In addition, the period over which their patenting activities are reflected in our database is specified. As is clear, not all of them are still active due to the large number of

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[21] The six top service companies which provide services and systems in different segments of upstream sector have been put in the category of integrated service companies, although the first three are often known as integrated service companies. Weatherford, Smith International, Dresser Industries were also added to this category because of their diverse range of products and services and also the similarity of their patenting behaviour. The scope of company activity is largely drawn from their websites and related Wikipedia. Apart from these 6 companies, other service and supply companies are classified as specialized supply and service companies, because they largely chose a particular scope of upstream activities.

mergers and acquisitions in upstream industry (grey in the table 4.6). The main M&A activities and their year of occurrence are also listed[22]. The patents of different affiliations of big companies are assigned to the parent company.

Some key insights from this table shed light on the characteristics of the innovation system of upstream petroleum. These top 50 patentees account for more than 50% of all patents in the sector. It is evident that six ISCs are ranked almost at the top of the list, holding nearly 43% of the share among Top 50s. The actual number of ISCs is currently 4 as the result of M&A activities. 16 IOCs are the second group in the list accounting for more than a 27% share. Their current number is 9 because of M&A activities that occurred in the late 1980s, 1990s and early 2000s.

The IOCs and ISCs together are responsible for a more than 70% share among the top 50 patentees. Apart from two R&D institutes with a share of nearly 6.5%, the rest (23%) is registered by 26 SSCs companies whose number also reduced to 15 because of M&As. Altogether, 30 entities from these 50 were active by 2009. According to this information, upstream oil and gas players have been major contributors to the upstream SIS, whether as ISCs, IOCs, SSCs or R&D institutes. Among these top 50 patentees, there are only 10 companies where their main business is not oil and gas, accounting for about 8 % of the innovation share.

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[22] The sources of this information are mainly company websites and related Wikipedia. A fuller summary of this information and the patenting trend of individual companies is available on request. There, it is specified how the data set has treated the companies after M&A activities. The simple rule is that major companies continued after M&A and smaller ones abandoned. For example, Exxon Mobile is a name assigned to Exxon after M&A and continued for the merged entity while Mobile is abandoned after 1999 when it was merged.

Table 4-6 Top 50 patentees in upstream petroleum industry over 1965- 2009 based on Derwent Innovation Index

Rank	Company***	Type*	IPF count	Active period	Main Business	Main M&A**
1	**Schlumberger**	ISC	3073	1966-2008	Integrated service company	1965 Forex(A); 1984 Sedco(A); 1985 Geco(%50A); 2000 Western Geophysical(%70A); 2006 Western Geophysical(%30A)
2	**Halliburton**	ISC	2560	1965-2008	Integrated service company	1998 Dresser(M)
3	**Baker Hughes**	ISC	1682	1968-2008	Integrated service company	1987 Hughes Tool Company(M)
4	**Shell**	IOC	1190	1966-2008	Integrated oil company	-
5	**Weatherford**	ISC	814	1973-2008	Integrated service company	1973 (F)
6	**Exxon Mobil Co.**	IOC	808	1965-2008	Integrated oil company	1999 Mobil(M)
7	**IFP**	R&D	749	1965-2008	Research institute in petroleum	-
8	**PRAD R&D**	R&D	638	1979-2008	R&D in particulate/multiphase processes	1979 (F)
9	**Texaco**	IOC	618	1966-2000	Integrated oil company	2001 Chevron(M)
10	**Smith International**	ISC	555	1969-2008	Supplies products to gas and oil production and exploration companies	2010 Schlumberger(M)
11	**Mobil oil corporation**	IOC	545	1967-2000	Integrated oil company	1999 Exxon(M)
12	**Dresser Industries**	ISC	456	1967-2004	Technology, products, and services used for developing energy and natural resources	1998 Halliburton(M); 2001 separation again
13	**Camco International**	SSC	409	1968-2002	Drill bits - Completion equipment	1998 Schlumberger(M)
14	**Vetco**	SSC	351	1968-2008	Oil and gas equipment, services	1991 ABB (Owned); 2007 GE(Ac. By)
15	**ConocoPhillips**	IOC	314	1966-2007	Integrated oil company	2002 Phillips(M);
16	**Chevron**	IOC	311	1966-2007	Integrated oil company	2000 Texaco(A)
17	**BJ Services Co.**	SSC	298	1965-2008	Pressure pumping and oilfield services	1974 Hughes Tool Company(Ac. By); 1989 dissolved to be part of Baker-Hughes;
18	**Sofitech**	SSC	273	1988-2006	-	1988 (F)
19	**Amoco**	IOC	271	1967-1998	Integrated oil company	2001 BP(M)
20	**Otis Engineering Co.**	SSC	257	1971-1992	Elevators, escalators and moving walkways	-
21	**Elf Aquitaine**	IOC	254	1968-2000	Integrated oil company	2000 Total(M)
22	**BP**	IOC	243	1978-2008	Integrated oil company	1998 Amoco (M), 2000 Arco(M)
23	**Cooper Cameron**	SSC	227	1984-2008	Pressure control, processing, flow control and compression systems	1989 Cooper(M)
24	**Statoil**	IOC	226	1983-2008	Integrated oil company	1972(F)
25	**Hughes Tool Co.**	SSC	224	1966-1992	Oil drilling rigs	1987 Baker(M)
26	**Dowell Schlumberger**	SSC	223	1980-2001	Pumping services for the oil industry	-
27	**FMC Corporation**	SSC	221	1968-2007	Pumps and subsea systems	-

28	**Marathon Oil Co.**	IOC	220	1965-2006	Integrated oil company	
29	**Arco**	IOC	217	1965-1999	Integrated oil company	2000 BP(M)
30	**M-I SWACO**	SSC	216	1989-2008	Drilling fluids (mud)	1999 (F)
31	**Western Atlas**	SSC	197	1977-2000	Geophysical services	1998 Baker Hughes (Ac. by)
32	**The Dow Chemical Co.**	SSC	194	1966-2007	Plastics, chemicals, and agricultural products	-
33	**Varco**	SSC	179	1978-2006	Oil drilling rigs	2005 National Oilwell Varco(M)
34	**Phillips Petroleum Co.**	IOC	177	1965-2002	Integrated oil company	2002 Conoco(M)
35	**BASF**	SSC	159	1969-2008	Chemical company	
36	**Total**	IOC	147	1968-2008	Integrated oil company	1999 Petrofina(M); 2000 Elf(A)
37	**National Oilwell Varco**	SSC	141	1986-2008	Oil drilling rigs	1987 (F)
38	**Hydril**	SSC	133	1967-2007	Pressure Control technologies	-
39	**NL Industries**	SSC	133	1968-1988	Component and chemical products	-
40	**Sandvik**	SSC	128	1977-2008	Tooling, stainless steel alloys and materials technology, mining and construction	-
41	**Kvaerner**	SSC	127	1982-2007	All facets of engineering and construction, including shipbuilding, process technology, engineering and construction	2005 Aker(M)
42	**ABB Offshore Systems**	SSC	125	1983-2007	Oil and Gas Equipment, Services	2004 Vetco(Ac. By)
43	**Union Oil Co. of California**	IOC	125	1965-2002	Oil operator	2005 Chevron(M)
44	**Rhodia**	SSC	119	1990-2008	Chemicals and new technologies	-
45	**Petrobras**	IOC	119	1983-2008	Oil operator	-
46	**Sumitomo Metal Industries**	SSC	118	1970-2007	Manufacturing Seamless Pipes and Tubes	-
47	**Christensen**	SSC	115	1969-1990	Directional drilling company	1987 Baker Hughes(Ac. by)
48	**Nalco Chemical Co.**	SSC	106	1967-2006	Chemicals and water treatment	-
49	**Baroid Indust. Dril. Products**	SSC	105	1975-1997	Drilling products and services	1991 Haliburton (Ac. by)
50	**Cooper**	SSC	100	1985-1993	Pressure control, processing, flow control and compression systems	1989 Cameron(M)

* ISC: Integrated Service Companies; IOC: Integrated Oil Company; R&D: Research and Development Institute; SSC: Specialized Service and Supply Company

** These M&A information come from Wikipedia and companies' websites and only cover the main ones. Therefore, they should not be accounted as exhaustive list

(A): Acquisition; (M): Merge; (Ac. By): Acquired by; (F) Founded in

*** Merged entities are in grey

These figures clearly show that a range of companies both from within upstream sector and outside are contributing to the knowledge base of the sector, but the role of oil business companies is dominant. In addition, public R&D institutes such as IFPs have been important players in the technological dynamics of the industry. The diversity of actors would be higher if we go down the list where other players such as universities and research laboratories are evident. Undoubtedly, petroleum industry is not a passive recipient of innovation offered by other industries. Companies from within the industry search for problems actively, carry out research and development programs, and shape the technological environment of the industry. Nonetheless, the sector also benefits from innovations offered by other relevant industries such as chemical, metallurgy and electronics.

Patterns of M&A activities also provide some interesting insights. One visible point is that they have been usually organized within either operators or service companies. In other words, operators have been targets for operators and specialized service companies usually targets for integrated service companies. With regard to the scale of oil operators, they could have targeted both integrated and specialized service companies, but our data does not show that this strategy has been attempted. This is particularly interesting for the post 2000 period because ISCs outperformed operators in financial terms, but operators did not consider their acquisition as a value adding activity. This signals that the domain of services is still conceived as a separate area outside of operators’ business, although it is technologically very advanced. Another related issue is that M&A activities within operators are usually clustered in time around the peaks in market dynamics characterized by oil prices. This is less so for service companies where their M&A activities are distributed more evenly over time. This pattern may suggest that M&As are more ‘market led’ for operators induced largely by low oil prices, while within the service sector, ‘technology led’ M&As are perused for innovation leadership.

4.7. Conclusion

This chapter had two main aims. First, to describe how upstream petroleum industry architecture has changed over time and to explain the major transformations in the industry. The purpose was to show historically how the companies’ division of labour in complementary markets formed and evolved over time. In addition, the possible driving forces behind the evolution of the industry architecture are discussed. It clarifies why certain division of labour emerged in one period and was replaced by a new pattern in subsequent periods. The second aim was to describe the sectoral innovation system in upstream petroleum. Within SIS approach dynamics, drivers and consequences of innovation are analyzed, and the knowledge base and the configuration of main agents involved in the innovation processes are addressed.

The analysis of transformations of the sector presented in this chapter clearly supports the advantage of the SIS approach to explain the innovation dynamics. It shows that there is no simple linear relationship between supply/demand factors and rate of innovation. The nature of supply/demand relationship with innovation may change over time through interactive and co-evolutionary processes creating new industry architectures. The dynamics of industry architecture is both shaped by and also affects the dynamics of innovation. As the case of upstream petroleum industry suggests, supply/demand factors could shape the industry architecture which affects innovation. Innovation also may affect supply/demand factors which could lead to alteration of industry architecture in the long term. SIS approach is relevant, because it takes an integrated, systemic view and considers complex interactive dynamics of different factors. The simple linear approach is not sufficient to explain the dynamics of innovation. The SIS approach which considers these interactive co-evolutionary processes is therefore very relevant to explain the transformations of upstream petroleum industry.

The main finding of this chapter is that upstream petroleum industry has experienced three distinctive phases since the early 1970s over which both upstream industry architecture and innovation systems changed. In fact the dynamics of industry architecture and systems of innovation are closely related and interconnected. The first period covers the early 1970s to the mid-1980s, the second period the mid-1980s to mid-1990s and the third period begins from the mid-1990s. Historical evidence suggests that the major driver behind the transition from the first to second period was collapse of oil prices and perhaps vertical industry divestures. The emergence of ‘qualitatively’ different demand for complex upstream projects in harsh and less accessible environments, combined with more-integrated industry architecture, were the major factors behind the transition from the second to third period.

The industry architecture of the first period was characterised by the historical dominance of integrated operators supplied by a different group of specialized supply and service companies. Geopolitical changes in producing countries and concerns of scarcity had pushed oil prices high, leading to the oil shocks of this period. While fears of scarcity motivated oil companies to look for oil reserves in geologically harsher and less accessible locations, high oil prices also provided resources to be invested in R&D. At the same time high oil prices channelled innovation demand by making economically feasible more technologically demanding reserves. Availability of financial resources for technological innovation and strong demand created a dynamic SIS characterized by high innovation growth and declining exploration and production costs. The relatively vertically integrated structure of the industry was supportive for large, high risk and long term R&D programs. These dynamics were successful in increasing supply and bringing down oil prices, thanks to innovation driven productivity, the trend that launched transition of upstream sector to the second period.

The industry architecture of the second period is characterized by consolidation among operators and also among service companies through M&A activities. Yet, a wave of vertical divesture and outsourcing by operators to specialized service companies happened. The main motivations were rationalization and refocusing for higher operational productivity. As a result, M&A activities of this period seems more of a ‘market let’ type and a response of financial markets to shrinking profits. The upstream SIS seems to stagnate in this period, when innovation took a negative trend. This low innovation performance is explained by low oil prices which not only reduced innovation investment, but also innovation demand. In addition, vertical disintegration of the value chain, or what Teece and Armour (1976) call divestiture, could have had a deleterious impact on R&D and innovation activities. Although low oil prices continued, innovation began a new take-off in the middle of the 1990s, expressing a new phase for upstream sector which could be called a 'technological revolution'.

The industry architecture of the third period is characterized by vertical integration and expansion of boundaries in major service companies. They also extended their project management and orchestration capabilities. This was driven by requests from their customers (i.e. operators) for more integrated and 'total solutions' to cope with increasingly complex upstream projects. The technological imperatives of these complex projects as a 'qualitatively' different demand triggered a 'technological revolution' of the sector in this period, in spite of low oil prices. Although 'market led' M&A activities among operators continued in this low oil price environment, M&A among service companies seems to be more 'technology led', enabling them to cope with technologically complex projects. The surge in the innovation trend and the nature of 'technology led' M&A activities among major integrated services companies over this period are interpreted as the signs of fundamental transformation of upstream sector towards higher technological complexity. Deeper examination of this proposition based on the patent data, however is the main aim of the next chapter.

A related theoretical conclusion is that standard application of the conventional industry life cycle (Abernathy and Utterback, 1978) is unable to explain innovation dynamics in an industry as mature as upstream petroleum. Industrial dynamics does not necessarily progress according to the standard s-shape models. Industry architecture may change in response to both external environment and firms endogenous strategies. New innovative agents may emerge within the sector and old players may replace their organizational boundaries or disappear from the sector. This process could be related to the emergence of new technologies, their integration with existing technologies and/or obsolesce of old technologies. This architectural dynamic and its relationship with technical changes are often overlooked in conventional perspectives. Given the simplistic and somewhat misleading view of this standard model, more systemic approaches such as sectoral innovation systems and industry architecture can provide deeper insights about innovation drivers and industrial dynamics.

Analysis of upstream sectoral innovation system in this chapter illustrates that it is a highly dynamic and innovative sector particularly in the most recent period. It shows that major disciplines such as mechanics, chemistry, physics and geophysics, electronics and even biology and biotechnology all contributed to the knowledge base of the sector. New technologies and products developed based on these knowledge sources are highly influential in shaping the industrial dynamics of the sector. In addition, the upstream petroleum knowledge base has considerable overlaps with other industries such as mining, polymer and plastics, instrumentation, electrical and communication, and chemical industry. My analysis of the main patentees confirms that the upstream industry is an active innovator. As a result viewing it as an only passive receiver of innovation from other sectors is wrong. A different range of operators, integrated service companies and specialized firms within the sector, in addition to non-firm organizations like public R&D institutes and universities are involved in innovation processes. Integrated service companies are positioned at top of the list signalling their critical role in innovation processes. The dynamics of innovation explored in this chapter suggests that industry architecture and technical change are interacting phenomena mutually shaping industrial dynamics.

5. Chapter 5: Dynamics of knowledge base complexity

5.1. Introduction

The aim of this chapter is to provide a meaningful representation of the knowledge base of the upstream petroleum industry in order to explore the dynamic of complexity in this sector. It was mentioned in chapters 1 and 3 that inadequate attention to the nature of knowledge underlying upstream petroleum industry is one reason why the innovative capacity of this sector is underestimated. I also suggested in the previous chapter that analysis of the industrial dynamics of upstream petroleum provides some evidence supporting the idea that the sector moves toward technological complexity to cope with a new 'qualitatively' different demand. We articulate and examine this proposition in this chapter using patent data.

Employing some of the latest developments in theoretical representation of knowledge and empirical methodologies suggested in the literature, I propose a three-dimensional perspective to characterise different aspects of knowledge base complexity. I argue that distinction and conceptual clarification of these three dimensions are important. Some of the conceptual ambiguities in the literature and inconsistent theoretical implications of each dimension can be resolved with regard to these three different aspects of complexity. Application of this three-dimensional perspective in the case of upstream petroleum industry confirms its usefulness in recognizing different phases of industry life cycle according to trends of complexity. It also shows that these three aspects do not necessarily follow similar dynamics, although they might be related to each other.

Combination of the dynamics of the knowledge base complexity presented in this chapter and technological opportunities presented in chapter 4 provide a more complete picture of the dynamics of technological regimes of the industry. The discussion about the implications of complexity for knowledge cumulativeness at the end of the chapter extends the picture of the dynamics of technological regimes. Understanding the combination of opportunities, complexity, and cumulativeness as three important elements of technological regimes paves the way for the analysis of associated dynamics of patterns of innovation at sectoral, organizational and geographical levels in subsequent chapters.

The analysis provided in this chapter involves three novel aspects. At the conceptual level, I expand and articulate the concept of knowledge base complexity in three dimensions. This is a neglected area in the SIS and technological regimes literature which requires more work, as explained in the chapter 3. In acknowledgement of this requirement I integrate insights from the endogenous complexity approach with the SIS approach and the technological regime idea. Accordingly, I develop a method to measure the dynamics of complexity which captures the three dimensions. The second novel aspect of this chapter is therefore of a methodological type.

The third novel aspect is the empirical application of the suggested method in an established industry. This is in contrast with all previous studies which are constrained to modern new sectors and general purpose technologies. Although theoretical discussions about knowledge based economy acknowledge that the increasing role of knowledge is not limited to the ‘new’ parts of the economy and cover the ‘old’ parts as well, empirical work on the knowledge base have given implicit priority to so called ‘knowledge intensive’ industries. This chapter is an attempt to create a more balanced approach. This is important because knowledge is the source of competitiveness, not just in particular industries but across the board in all economic activities (Antonelli, 2011).

Section 5.2 is a brief review of the development of theoretical approaches in the literature about how to represent and model knowledge. Section 5.3 summarizes the state of the art in empirical analysis of the sectoral knowledge bases. It explains the previous empirical attempts to provide a meaningful representation of the knowledge base in different sectors. Section 5.4 provides a dynamic and three-dimensional perspective to knowledge base complexity, distinguishing between three dimensions of depth, breadth and systemic complexity. It also proposes a methodology to measure each dimension of complexity. I briefly introduce the hypothesis and the data used to capture the dynamics of knowledge base complexity in upstream petroleum industry in the section 5.5. The results of the analysis are provided in the section 5.6. Section 5.7

discusses the knowledge based perspective to industry life cycle according the results presented in section 5.6. The last section summarises the findings and concludes.

5.2. Theoretical approach to the knowledge base

As the importance of technological knowledge and innovation in economic activities is increasingly understood, scholarly efforts towards more meaningful and sensible representation of knowledge have increased. The result has been the development of different approaches which have progressively improved our understanding of knowledge production and utilization processes and their economic consequences. In an original literature survey, Krafft and Quatraro (2011) proposed a taxonomy differentiating four theoretical approaches to knowledge. They showed how these approaches have developed over time from linearity to endogenous complexity. They concluded that endogenous complexity is the last and most promising approach, although it is still in its early stages. Among other important features, what makes it attractive and relevant to this research is its representation of knowledge as an emergent dynamic property of the system which can change and evolve over time. This approach is consistent with the dynamic perspective to technological regimes and the properties of the knowledge base presented in chapter 3.

The weakness of previous approaches is that they either look at knowledge as homogenous capital stock or they assume the architecture of knowledge structure as given, exogenous and stable over time. The first approach to model knowledge and analyse the economic impact of knowledge production was *the extended version of production function* (Solow, 1956 & 1967; Griliches, 1979; Mansfield, 1980). Knowledge is seen as a new input to production function, in addition to labour and fixed capital. Similar to capital, knowledge is also viewed as homogenous stock accumulated as the linear outcome of R&D investments. The most recent developments in this strand of research extents the definition of capital to include knowledge accumulation and capture its role in productivity growth (Corrado et al., 2005, 2009).

The next approach was *knowledge production function* which was proposed in the late 1980s and early 1990s (Nelson, 1980 & 1982). The aim was to open the black box and capture interactive dynamics leading to production of technological knowledge.

Although it keeps the homogenous capital stock conception of knowledge, it takes into account the role of increasing returns stemming from learning processes and knowledge externalities in knowledge production processes. Nonetheless, little seems to be said about the cognitive micro processes involved in the production of knowledge.

Recombinant knowledge is the third approach, developed to explain micro mechanisms underlying knowledge production activities by integrating complexity sciences and economic theories. New knowledge is seen as the outcome of a search process over a rugged landscape with the aim of finding a local optimal combination among a set of alternative components. Complexity and heterogeneity of knowledge are both acknowledged, because knowledge is comprised of many interacting different elements. Although this recombinant approach provided very interesting insights, complexity of the system is still given and exogenous. This feature is not appropriate for analysis of evolutionary processes and dynamics of technological changes and complexity is an emergent and endogenous property of the system (Frenken, 2006).

The latest approach to technological knowledge is *endogenous complexity* assuming that architecture of a complex system may change over time, as a result of internal dynamics of the system. In this view, knowledge is represented as an emergent property stemming from complex dynamics and interactions between elements of the system. They could be the bits or elements of existing knowledge (Saviotti, 2007; Antonelli, 2008; Arthur, 2009).

A general representation of knowledge has been suggested (Saviotti, 2004, 2007, 2011) as the theoretical base for recent empirical studies of the knowledge base within endogenous complexity framework (e.g. Quatraro, 2009; Krafft et al., 2011). The general characteristic of this representation allows its application for different types of knowledge produced by different institutions. The main advantage of this representation is the powerful basis that it provides for empirical analysis of properties of knowledge creation and utilization processes using information in patent documents or publications.

Two properties of knowledge are at the centre of this representation (Saviotti, 2004 & 2007):

1- Knowledge is a co-relational structure:
2- Knowledge is a retrieval or interpretative structure.

The first property implies that knowledge establishes co-relations, or linkages between different concepts and variables in order to offer an understanding (scientific knowledge) or create a utility or functionality (technological knowledge). The second property implies the possibility of recovery of the types of knowledge which are close and similar to what an agent already knows. This feature refers to the involvement of actors' absorptive capacity in knowledge development processes (Cohen and Levinthal, 1990). In other words, agents in a dynamic economic system need to absorb new knowledge. However their existing internal knowledge determines their capacity to learn external knowledge and to use available information (Krafft and Quatraro, 2011).

It can be deduced from these properties that knowledge has a collective character and could be represented as a network, nodes of which are concepts or variables, connected together when they are jointly used in the knowledge space. This general representation is consistent with the endogenous complexity approach, because new knowledge could be the outcome of creative recombination of heterogeneous bits of knowledge which are fragmented and belong to different economic agents. In this network view, the knowledge base at each point of time is characterized by a structure or system formed of a set of elements (or nodes) and their relations and interactions (links).

This particular structure should be seen as both effect and determinant of the interaction among agents implying the collective character of knowledge. In this representation, the structure of knowledge, as a complex system, is shaped by and also shapes agents behaviour. This structure may change over time as a result of introduction of new bits of knowledge or emergence of new links and combinations. It also may change when the importance of some nodes or links change in the architecture of the network. Agents' behaviour, which depends on their absorptive capacities and learning dynamics, could change when they activate their search processes in this knowledge landscape. They often move in the spaces very close to their learning capacities. On the other hand, agents' behaviour could change the structure of the knowledge base, as they may introduce new bits or linkages and drop old ones. Therefore, technological change is an outcome of interactions between knowledge structure level and agents' level.

The collective character of knowledge can be mapped at different analytical levels, from firms, to sectors, regions etc., depending on the analytical purpose of the study. At the firm level, the collective character is the outcome of interactions among individuals and different departments within the same firm. The knowledge base of the firm could be defined as the collective knowledge (all bits of knowledge dispersed within the firm) used to achieve productive goals. When we aim to study of the knowledge base of a sector or an industry, this collective character also includes the interactions among different agents involved in knowledge generation processes in that sector. Accordingly, the knowledge base of the sector is defined as the collective knowledge according to which the sector operates in order to deliver particular goods or services.

5.3. Empirical studies of sectoral knowledge bases

The network representation of knowledge has offered a suitable conceptual foundation for the study of dynamics of the knowledge base of the firms and industries (there are several examples in Saviotti, 2011). However, it is practically difficult to identify all the nodes (variables) and links (relationships) of the knowledge base of a firm or a sector. As a result, the empirical emerging research tradition often suggests identifying small units within traces of knowledge, as an approximate and alterative strategy (Saviotti, 2004, 2007, 2011, Krafft et al., 2011). Patents and publications are regarded as the most available and accessible traces of knowledge within which these small bits of knowledge appear systematically. They have become the main basis for recent empirical quantitative studies of the knowledge base.

Technological classifications or themes appear in patents and publications are employed for representation of knowledge network. Technological classes or themes represent the nodes, because they are indicators of the main units of knowledge. Joint utilization of the units in the same text such as patents or publications is also interpreted as the indication of links between bits of knowledge. This implies that both units are complementary parts of a piece of knowledge, neither of which alone could do the job of the collective entity. Therefore, co-occurrence of technological classes in the same patent document shows the link, while the frequency of co-occurrence of different classes is a measure of strength of the link. The matrix of co-occurrence of technological classes could define the knowledge network where the generic cell is the observed frequency of co-occurrence of technological classes at a particular point of time. This matrix provides the raw material for calculation of different characteristics of the knowledge base (Krafft et al., 2009; Antonelli et al., 2010).

A similar approach is followed in this study in order to identify the dynamics of knowledge base of the upstream sector. This approach offers a number of valuable and promising contributions, although it is relatively very young and so far applied only in a few studies. At a general level, we can identify firm and sectoral studies of the knowledge base. The former group has been developed more, while the second is still at exploratory stages.

In firm level studies, different measures of the knowledge base are often suggested as independent variables where their capacity to explain knowledge, innovative or economic performance of firms is examined. Knowledge coherence, knowledge relatedness or knowledge integration (Breschi et al., 2003; Nesta and Saviotti, 2006 & 2006; Nesta, 2008, Dibiaggio and Nasiriyar, 2009) and knowledge decomposability (Yayavaram and Gautam, 2008) are some of the suggested features of the knowledge base. They are all computed using matrices of co-occurrence of technological classes.

The second group has mostly focused on exploration of the dynamics of the knowledge base in industries and their possible associations with industry life cycles (Grebel et al., 2006; Krafft et al., 2009 & 2011). Antonelli et al. (2010) is one different study which takes a cross-country approach to study the properties of the knowledge base of the ICT sector in different countries and examine its relationship with countries' productivity growth.

From the perspective of the present PhD thesis, the first noticeable point is the exclusive focus of all previous studies of sectoral knowledge bases on so-called *knowledge intensive sectors* such as biotechnology, telecommunication, electronics (Grebel et al., 2006, Krafft et al., 2009; 2011) and ICT (Antonielli, 2010). In this line of research, Grebel et al. (2006) is perhaps one of the earliest attempts which aimed to explore the life cycle of knowledge intensive industries. The broad claim is that changes of industrial organization in biotechnology and telecommunications sectors during the

1980s from vertically integrated firms to innovation networks can be explained, at least partly, by changes in the sectoral knowledge bases.

Knowledge dynamics were the result of technological paradigm shifts and a growing rate of creation of new knowledge which stimulated specialization among different firms and institutions. It is argued that most industry life cycle models are proposed based on industries of the first half of the twentieth century, when the *visible hand* of Chandlerian vertically integrated firms was the appropriate form of organization. However after the 1970s, emergence of radically new types of knowledge created a large discontinuity in the knowledge base of the sectors. It altered the industrial organization of these sectors toward a more disintegrated and network based configuration (Grebel et al., 2006).

Employing a co-occurrence matrix of technologies, it is shown that firms' search strategies evolve from *random search* immediately after the discontinuity, to a more *organized search* later on (Grebel et al., 2006). In the former condition, firms perceive new technological opportunities involved in the new paradigm, but they have not still identified promising trajectories of future developments. Uncertainty is high and firms try all possible directions and combinations. As a result we expect that agents focus more on *exploration* search strategies where innovations tend to be of a more radical kind. This implies investment in various ranges of combinations reflected in more equal distribution of co-occurrence frequencies in the matrix.

After some period of learning, firms begin to identify the most promising trajectories and the most productive combinations. Uncertainty reduces and search becomes organized around a more limited number of options and their recombinations on well defined trajectories. The agents employ more *exploitation* search strategies in order to enhance their benefits from the new knowledge discovered in exploration phase. This situation implies more concentration on some promising combinations. It is reflected in a few high-frequency cells in co-occurrence matrix. This dichotomy clarifies March's (1991) well known distinction between *exploration* vs. *exploitation* strategies (Krafft et al. 2011).

Subsequent work (Krafft et al., 2009, 2011) suggested viewing these dichotomies as corresponding to a lifecycle, providing further analytical refinements using more sophisticated measures. The lifecycle is supposed to begin with the birth of new types of knowledge and continues until it gradually matures and becomes routine. The implication of this perspective is that exploration vs. exploitation should not be viewed as two discrete states, but rather the extremes of a range of possible combinations. Several measures such as *variety* (in two types related and unrelated); *coherence* and *cognitive distance* are suggested to improve the analytical capacity of the previous dichotomies and to capture the dynamic of the knowledge base.

The empirical results broadly support the previous hypothesis of transition from random to organized search, but provide greater articulation with reference to trends of the measures of the knowledge base. Multiple patterns could emerge out of the combination of these measures, corresponding to each phase of industry life cycle. For example, a high ratio of *related variety* to *unrelated variety,* which is expected in the exploitation phase, is compatible with high, constant and growing coherence. This implies that there is no one-to-one correspondence between values or trends of knowledge base properties and phases of industry lifecycle. Different sectors present different patterns of transition in terms of timing, levels and trends of different properties of the knowledge base (Krafft et al., 2009, 2011).

While providing fascinating results, this very new strand of research is still at explorative stages and most results are very descriptive. We need further extensions in several aspects. The authors (Krafft et al., 2009) proposed more explanatory work as the future avenue of research. First, examination of the impact of change of knowledge base structure on the patterns of industrial organization, especially entry to and exit from the sector. Second, analysis of geographical concerns and challenges of companies in knowledge generation processes over long distances. In other words, how the nature of knowledge may affect patterns of geographical organization of innovation. In addition, the comparison of the results with other industries has been recommended to broaden the empirical base of this new strand of research. (Krafft et al., 2009; Krafft and Quatraro, 2011).

This PhD thesis is a step forward which meets all three suggestions. The previous studies have all focused on new and so-called knowledge intensive sectors. Therefore, other industries are implicitly considered less important or as downgraded sectors in today's knowledge based economies. Focusing on a currently established and old sector - upstream petroleum industry - is empirically one of the novel dimensions of this PhD research. In addition, I follow theoretically both the sectoral and geographical implications of the dynamics of complexity of knowledge base structure and examine them empirically using patent data.

5.4. knowledge base complexity: A three-dimensional perspective

I began this research on knowledge base complexity with a relatively simple view on the concept. I got the first definition from the SIS literature defining complex knowledge as what involves combination of large number of technological disciplines and organizational competences (see chapter 3, section 3.4). However, more digging in relevant literatures showed that it is neither a straightforward concept to define nor an easy concept to measure. In fact the term complexity is itself a 'complex' concept with several definitions and dimensions according to different authors.

The term complexity is an increasingly popular concept, partly because of the rapid diffusion of complexity theory as a general approach into many disciplines in both natural and social sciences. This concept could be ambiguous and confusing, because different authors point out different types (for example, static vs. dynamic), dimensions (for example breadth vs. depth or both), levels or functions (component vs. system; product vs. process; firms vs. industries) of complexity. They also take different perspectives to complexity (for example ontological vs. epistemological), while sometimes not explicitly clarifying what kind of complexity they are talking about.

Even within the economics of innovation and knowledge as a new discipline, there is no unified definition of complexity and its measurement approach. For the purpose of this study, I identified three dimensions of complexity relevant and interesting for the analysis of knowledge base as a system: breadth, depth and systemic. Conceptually, they refer to three different dimensions of the structure of the knowledge base. Breadth and depth describe the characteristics which are related to the elements of the knowledge system, but do not take into account the interdependencies and relationships between elements. In contrast, systemic complexity characterises how different elements of the system are connected. In what follows I provide a definition of each dimension and a relevant proxy to measure them in this research. These definitions are drawn from available literature and refined for further clarification and distinction. Although the three dimensions are different conceptually, they are not necessary totally independent. It means that change of one dimension could have particular implications for other dimensions.

5.4.1. 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. At first glance, breadth complexity appears simple, referring to the *diversity* of elements of a system such as knowledge base of a sector. However Stirling (2007) explains that this concept could refer to three different properties: *variety, balance and disparity*[23].

According to Stirling (2007), the first property is *variety* or the number of categories. When we ask about this property, we normally need to answer the question *"how many types of things do we have"* (Stirling, 2007, p. 709). The concept of *balance* answers the question *"How much of each type of things do we have"* (Stirling, 2007, p. 709). This property refers to *balance* or distribution of things or elements within categories. In some categories or technological classes, we might have a few, but in others we might have many. *Disparity* is the other property which is different from the previous two. It aims to respond the question *"How different from each other are the types of things that we have"* (Stirling, 2007, p. 709).

Unfortunately there is no consistency in using the terms for different properties. *Balance* for Stirling (2007) which describes the distribution within categories, is also referred to as *variety* by others (Frenken et al., 2007; Krafft and Quatraro, 2011). In this research, I reserve the term *variety* for this distributional property, because it is a more important aspect. This application of the term has recently become popular in both

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[23] Stirling (2007) and Rafols and Meyer (2010) use 'diversity' as the umbrella term covering the three properties of breadth complexity

economic and innovation studies (for example Krafft et al., 2009; Saviotti and Frenken, 2008, Boschma and Iammarino, 2009; Neffke et al., 2011). *Variety* is very important in the study of sectoral knowledge bases, because technical knowledge usually has highly skewed distributions (Saviotti, 2009). In each sector, certain core technological areas are very important, while many others have a very marginal role in the knowledge structure.

Most breadth studies have been performed at firm level in order to understand how and why companies are technologically diversified and how their pattern of specialization may change. For example, breadth of knowledge base has been analyzed in pharmaceutical companies (Brusoni et al., 2005; Brusoni and Geuna, 2005; Nesta and Saviotti 2005) and tyre companies (Acha and Brusoni, 2005). The number of fields or classes in which a firm is active or relatively 'specialized[24]' is considered as the breadth of firms' knowledge bases.

In this research, my focus is on the dynamics of *variety* to describe the evolution of breadth complexity. Therefore, I do not analyze other diversity or breadth properties. This is because *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. From time to time, not only are new technologies added to the knowledge base, but also the share of different technological fields might change. Some technological areas might involve rich opportunities and expand. Others might be tried and later relinquished. More importantly, the size and scope of search strategies could change over the industry life cycle, shaping the technological trajectories of the sector, as explained in section 5.3.

A number of indicators have been suggested to capture the *variety* or dispersion of technologies within categories. The common principle in all of them is that ceteris paribus, the more equal the distribution, the higher the *variety*. For example, the Herfindahl index is very popular in studying technological *variety* (for example Quintana-García and Benavides-Velasco, 2008; Corrocher et al., 2007; Garcia-Vega, 2006; Gambardella and Torrisi, 1998; Granstrand and Oskarsson, 1994 among many

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[24] The indicator of relative specialization is often 'Revealed Technology Advantage (RTA) and its variations which will be explained in the next chapter.

others). Nonetheless, I employ the Entropy index to measure variety as a proxy for breadth complexity, because of some advantages.

Entropy is an old index borrowed from information theory in thermodynamics (Prigogine and Stengers, 1984) and used in diversification studies (for example Granstrand and Oskarsson, 1994; Kodama, 1986). This index measures the degree of disorder or randomness in a distribution where more balanced distributions get higher values. More recently, it has been used in research on the dynamics of sectoral knowledge bases (Krafft et al., 2009 and 2011). The main advantage of this index is its decomposability to 'within' and 'between' parts enabling us to study both *related variety (RV)* and *unrelated variety (UV)*, at the same time. Unrelated variety refers to the degree of disorder or variety 'across' the main categories (aggregated level), while related variety captures the sum of the weighted entropy or the average degree of disorder 'within' categories (at disaggregated level) (Frenken et al., 2007).

This feature allows us to explore the sources of dynamics in breadth complexity measured by the *total variety (TV)* index. The variety of sectors could change as a result of change in both local and global search boundaries. In the case of a more local 'organized' search, companies diversify in the vicinity of available technological fields, leading to higher disorder 'within' technological classes or higher *related variety*. Conversely, when search processes are more 'random' and global, *unrelated variety* increases. As the total level of the sectoral variety is the sum of the two components, we could trace the changing trend in organized vs. random search strategies and how the mix of the two changes over time.

For formal notification, let C_g refer to technological classes at the 4-digit level where g = (1, …, G). All sub-classes i at disaggregated level (7-digit here) fall under one 4-digit classes, because of the nature of hierarchical classification system. Therefore the share of 4-digit classes P_g is given by the sum of p_i shares:

$$P_g = \sum_{i \in C_g} p_i$$

Unrelated variety is drawn from the entropy index formula based on the shares at the 4-digit level (P_g):

$$UV = \sum_{g=1}^{G} P_g \ln\left(\frac{1}{P_g}\right)$$

Related variety is the weighted sum of entropy for shares of 7-digit sub classes (p_i) ‘within’ each 4-digit class, given by:

$$RV = \sum_{g=1}^{G} P_g V_g$$

Where **:**

$$V_g = \sum_{i\in C_g}^{G} \frac{p_i}{P_g} \ln\left(\frac{1}{p_i / P_g}\right)$$

Given the decomposability feature of the entropy index (Frenken et al., 2007), the *total variety* (TV) entropy is given by the sum of *unrelated variety* (UV:4-digit entropy) and *related variety* (RV: weighted sum of 7-digit entropy within each 4-digit classes).

$$TV = UV + RV$$

To sum up, among the three aspects suggested for breadth complexity, I chose to focus on *variety* referring to the degree of randomness or balance of innovative activities among different technological categories. The *total variety (TV)* is measured by the entropy index. This index is decomposable into two components *of related (RV) and unrelated variety (UV)* which distinguish different sources of *total variety (TV).* Related variety captures the degree of local variation and differentiation within technological categories. Unrelated variety looks at global differentiation across technological categories. Since the total variety is the sum of these two components, its trend may change as a result of either of the two components. The relative share of the two components in the overall trend of total variety could show the dominant search strategies in each period (Krafft et al., 2009 and 2011).

5.4.2. Depth complexity

The issue of depth complexity is more controversial and less straightforward, because of the lack of agreement on the definition of the concept and also limited studies referring to depth and its measurement methodology. For example Brusoni et al., (2005) defines the depth of knowledge for a firm in a particular field as the integration of both basic and applied research in that field. The total depth of knowledge for a firm is considered as a proportion of all the fields in which the firm is specialized, both in terms of basic and applied research. Another study suggests the count of secondary technological fields of each patent as the measure of depth of patent or invention, when they are the same as the main technology field of the patent itself (Özman, 2007). In fact this method first measures the depth of each patent according to its secondary classifications, the average of which defines the depth of knowledge base at higher aggregated levels for such firms or industries.

In order to choose an appropriate index for the depth complexity of knowledge at industry level, we first need a relevant conceptual definition with regard to the purpose of the study. While breadth of sectoral knowledge refers to the range of different technical fields, depth is more about *accumulation* of knowledge within 'existing' fields vs. technological discontinuities which may *invalidate* (or destroy) the value of existing knowledge. In short, breadth is concerned with heterogeneity while depth addresses the level of sophistication and accumulation within a particular area. This approach is in line with the Wang and Tunzelman (2000) definition, referring to "analytical sophistication of a subject, which becomes complex because of the cognitive difficulty of pushing the particular matter to its logical extremes" (p. 806).

Although in practice it might be difficult to distinguish between two types of knowledge development through breadth (broadening) vs. depth (deepening), conceptually it is informative to address them differently. Particularly, it can be meaningful in comparative terms where the knowledge base of some industries is being developed with new technologies (broadening), while others mostly focus on certain core technological fields digging more within existing technological fields. While these two processes of knowledge expansion are often active side by side, their importance and weight could change over time in a particular industry.

According to these conceptual concerns, we need to know the degree to which new knowledge in the upstream petroleum industry is generated within existing old technological areas vs. totally new technological fields. As a result, the measure of depth complexity is simply defined as the percentage of knowledge added to the industry knowledge stock from existing technological classes. Formally, we assume that ΔK is the extent of knowledge generation in the knowledge base of the sector. ΔK_{old} is the extent of knowledge generation from existing technological classes in a previous period. ΔK_{new} also is the amount of knowledge added from new technological classes which were not present in the previous year. Therefore, the sum of the two forms the total knowledge added to the knowledge stock of the sector between two subsequent years.

$$\Delta K = \Delta K_{old} + \Delta K_{new}$$

Accordingly, depth complexity is given by the Knowledge Accumulation Percentage from old technological classes:

Knowledge Accumulation Percentage (KAP) =($\Delta K_{old} / \Delta K$)*100

This index could be interpreted as a proxy of sectoral cumulativeness and its changing pattern over time. In one hypothetical extreme, if all additional pieces of knowledge are from existing fields, depth would be at its highest level of one. On the other hand, if all increased knowledge comes from new sources, the depth would be zero, meaning a lack of contribution of existing fields in the knowledge expansion process of the industry. Given the incremental cumulative nature of knowledge generation processes, we normally expect a high and increasing trend when industry moves toward maturity. However, rapid technological revolutions may invalidate the old knowledge reducing cumulativeness. But this mostly happens at the level of individual technologies. At the level of a sector, it is hardly possible that a large proportion of knowledge comes from totally new fields.

5.4.3. Systemic Complexity

Most of the time when scholars talk about complexity, the main concern is 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). When this kind of complexity matters, *recombination* of both pre-existing and new bits of knowledge is key for the generation of new knowledge and introduction of systemic innovations (Chesbrough and Teece, 1996).

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), I label this type of complexity as *systemic complexity*. This dimension of complexity is more in line with the perspectives developed in complexity sciences such as Simon (1962) and its integration in the economics of innovation (Antonelli, 2011). This is because in the complex systems perspective, the interactions between different elements of the system which could create endogenous non-linear dynamics are at the centre of the analysis.

The proxies discussed so far do not consider the links and interactions between different elements of the knowledge base; therefore they do not capture the dynamics of systemic complexity. They do not consider the recombinant nature of the knowledge and its endogenous systemic complexity. In order to measure this type of complexity, network representation of the knowledge base is very relevant. As explained in section 5.2

(Saviotti, 2009, 2011; Krafft, 2011), the knowledge base has a co-relational structure comprised of nodes and links between these nodes. In this approach knowledge could be represented as a network.

If the knowledge base of the industry is conceptualised as a network, nodes are technology classes and links represent relationships between technologies connecting nodes together. The measures of breadth and depth complexity introduced so far do not consider the connectivity and the relationships between technologies. In other words, they just represent the variety and size of the nodes of the knowledge network, but they ignore the structure of relationships between different knowledge domains. Even related variety captures the level of diversity or disorder around key technologies, but does not consider how different technologies are connected and related in the knowledge network. In order to provide a fuller representation of knowledge base from a systemic complexity perspective, we need to know how the structure of the network is formed by linkages. Dynamics of complexity could be understood, not only through changes in the number and size of the nodes (which refer to breadth and depth complexity), but also from the pattern of linkages and interactions between the nodes (which refer to systemic complexity).

Systemic complexity or network connectivity may change as result of formation of new ties between un-connected nodes or a stronger relationship between connected nodes. It also may change when isolated nodes appear or connected nodes are disconnected. The main advantage of network analysis indicators is that they consider knowledge as an integrated system in which both the building blocks of the system (nodes) and their interactions (ties) are investigated at the same time. This enables us to monitor how knowledge structure changes over time when new technologies emerge, diffuse and integrate in the system or the old ones expire, are abandoned or disconnected from the knowledge base (Krafft et al., 2011).

Social Network Analysis (SNA) has a powerful toolbox to characterize the connectivity of the network. As mentioned in section 5.3, a matrix of co-occurrence of technological classes has been suggested as a raw material on which different features of the knowledge network could be measured. Among various measures available to describe the connectivity and structure of the knowledge base, network *density* is one of the popular indexes. It describes the general level of linkages to nodes of a graph, defined as the total number of links as a proportion of the possible number of links between nodes. However the weakness of this measure is that it does not consider the *strength* of the nodes and links, and treats weak and strong links equally (Krafft, 2011). From previous research, we know that distribution of the links is highly unequal. A few nodes are very central and highly connected, while many others have very weak linkages or are isolated (Saviotti, 2009, 2011).

The *degree* of a node is used as one of the centrality measures, describing how strong is the level of connectivity of a node. Formally, the following equation expresses the measure of *degree centrality (DC):*

$$DC_n = \sum_{i \in N \neq n} l_{ni}$$

Where ***n*** represents the nodes and ***l*** represent the links.

The *degree centrality* is defined as the number of links of one node with other nodes of the network. Because this measure is affected by the network size, it is often divided by its maximum value to provide a normalized proxy (Krafft, 2011), as the following equation shows:

$$NDC_n = DC_n / (N - 1)$$

This normalization allows for comparability of the degree centrality over time and analysis of dynamics of systemic complexity, because the size of the knowledge network changes over time. *Degree centrality* characterises a single node, not the network. 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), I 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:

$$WADC = \sum_{n} [NDC_n * (P_n / \sum_{\mathrm{n}} P_n)]$$

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

5.5. Hypothesis and Data

We expect that these three measures of different dimensions of complexity provide a meaningful base to answer the first question of this PhD thesis:

Q1: How has the technological complexity evolved over time in the upstream petroleum industry?

Accordingly, our first basic hypothesis is that:

Hypotheses 1: Upstream petroleum industry has gradually moved towards higher degrees of technological complexity.

We aim to evaluate this hypothesis in upstream petroleum industry with reference to the three-dimensional perspective to knowledge base complexity. The discussion of complexity in the previous section showed that complexity could have several dimensions. As a result, a precise answer to the question requires defining which dimensions of complexity are relevant. We suggest that the distinction between breadth, depth and systemic complexity offers analytical value and removes some of the conceptual ambiguities in the literature. We also discuss the different theoretical implications of the different dimensions of complexity in the next chapters.

In theory, it is perceivable how the knowledge base of an industry could move towards higher degrees of complexity via any of these three mechanisms. When a new piece of knowledge is generated within *incumbent* technical domains, depth complexity increases. If a new piece of knowledge is generated in a *new* technical domain, breadth complexity increases. If a new piece of knowledge is the outcome of linkages and relationships between several knowledge domains, systemic complexity of the sectors increases. Nonetheless, these mechanisms are often combined in practice. Using the suggested measures of three dimensions of complexity, we explore dominant trends in upstream petroleum industry and investigate their connections with the industry life cycle.

The three suggested proxies are measured based on the international patent classification system (IPC) and the matrix of co-occurrence of technological classes. Table 5.1 displays some basic descriptive statistics at 4-digit and 7-digit levels of aggregation. Given the decomposability nature of entropy index for breadth complexity, these two levels of aggregation are used to measure the dynamics of total variety (TV) at 7-digit level and related and unrelated variety (RV & UV) at 4-digit level. The table shows that on average every 4-digit class is formed of more than seven sub-classes at 7-digit level. In line with previous research (Krafft et al., 2009, 2011), we assume each pairs of entities (in this case patents) in one class are on average more similar in terms of knowledge domain, than those which are classified in different classes. Although some exceptions might exist, this seems a reasonable assumption without which the whole classification system would become meaningless.

Table 5-1 Descriptive statistics at different digit of IPC classes

Level	Class count	Mean	Std. Dev.	Min	Max
4 dig IPC	600	125.93	1019.50	1	23921
7 dig IPC	4301	27.69	217.59	1	9304

Since the focus is on *dynamics* of the knowledge base complexity, periodical analysis of the trends is important. The main three periods of the industry are labelled as p1, p2, p3 for simplicity, as explored in the previous chapter. Following other trend analysis research in the field (e.g. Krafft et al., 2009), 5-year cumulated data are used to smooth the random changes and introduce some rigidity to the trends.

5.6. Dynamics of knowledge base complexity in upstream petroleum

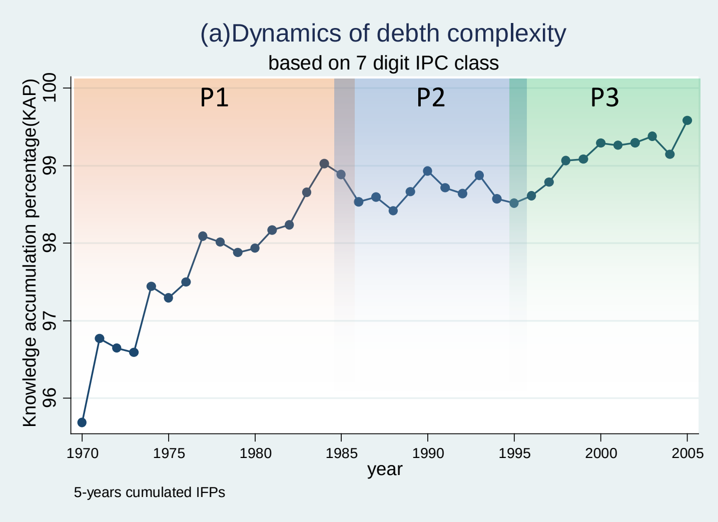
The dynamics of three dimensions of knowledge base complexity in the upstream petroleum industry are presented in figure 5.1. The trends clearly show that the three dimensions follow different patterns reflecting three different aspects of complexity phenomena. Some broad trends are observable in all three dimensions which could be understood with reverence to major transformations of the industry. Figure 5.1 (a) shows the dynamics of depth complexity capturing the degree of cumulativeness of the upstream sector. It presents the Knowledge Accumulation Percentage (KAP) in existing technological classes, compared to new classes.

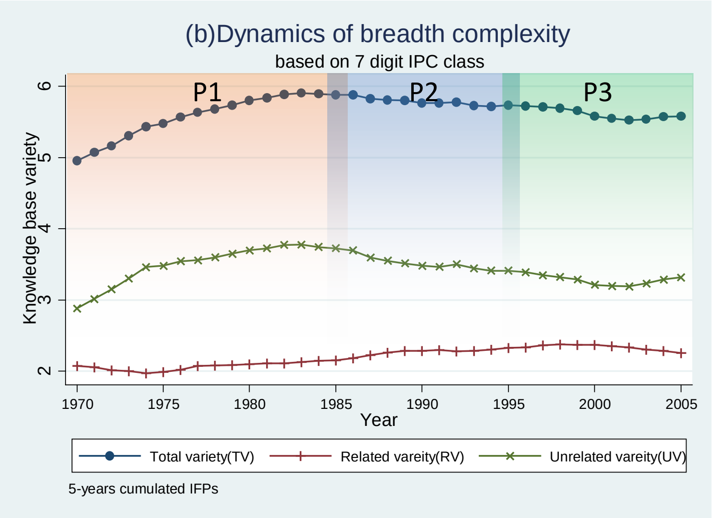
The trend of depth complexity indicates the very high and growing level of cumulativeness. It suggests existing knowledge in the current technological classes is a major contributor to the expansion of knowledge stock in the industry. In contrast, new technological fields are playing a tiny role in the growth of the knowledge base and this marginal role is decreasing.

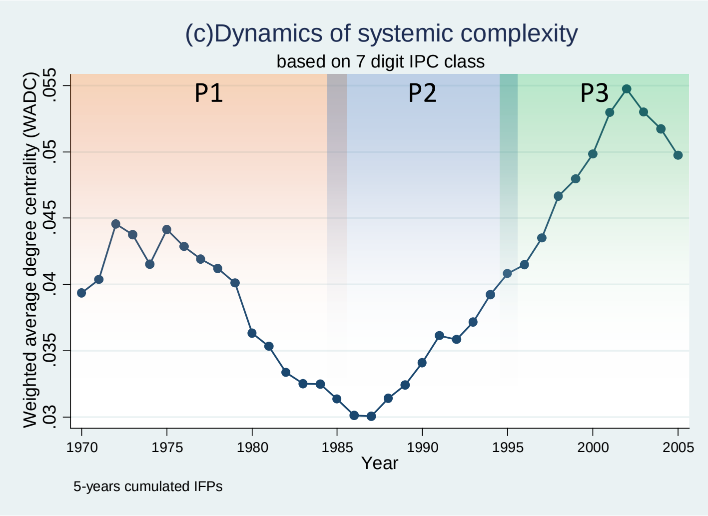
While depth complexity has an overall increasing trend, it seems that the trend stabilized temporality over p2. One consistent interpretation of the overall rising trend is that as time goes by and the industry approaches maturity, the size of the knowledge base expands. This is clear from the increasing size of innovative activities and accumulated knowledge stock in the sector. As a result, the relative share of new technological areas compared to accumulated knowledge decreases. Unless the industry experiences a radical and pervasive technological discontinuity, it is intuitive to expect that the large share of new knowledge comes from existing known sources. This reflects the local character of knowledge where existing available knowledge is a prerequisite of knowledge generation processes (Saviotti, 2007).

What seems counter intuitive is that the rising trend of depth complexity stalled over p2 when industry was in low opportunity condition. We normally expect less investment in very new high-risk technological areas in non-favourable conditions and relatively increasing concentration in less-risky previously known knowledge domains. One explanation might be that under high technological opportunity periods (p1 and p3), new opportunities are increasingly explored more in and around existing technological areas.

Figure 5-1 Dynamics of the three dimensions of knowledge base complexity in upstream petroleum industry







Therefore, innovators tend to allocate an increasing share of their effort and more resources to existing technological areas, as reflected in the rising trend of depth complexity. When such incentives and resources are not available, the level of depth complexity stays stable. As a result, we may conclude that depth complexity could have a direct relationship with the innovation opportunities, if there is no radical technological discontinuity in the sector. The higher the number of innovation opportunities, the higher the level of cumulativeness of knowledge at a sectoral level.

The trends of breadth and systemic complexity in figure 5.1 (b) & (c) present broadly two-phase patterns. They seem related, yet moving in opposite direction, with a transitional period in early p2. Total and unrelated variety (breadth complexity) expresses an upward trend over p1. After achieving their peaks in early p2, they turn to a downward trend over p3, when related variety takes an upward trend. 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 (section 5.2), we know that variety represents the nodes, while systemic complexity represent the links and the connectivity of the network.

The observed patters are very similar to the proposition of previous studies that after a discontinuity we expect to observe emergence of new nodes in the knowledge network, followed by a wave of formation of new links (Saviotti, 2009 & 2011).

The total variety (TV) begins with an upward trend over p1 which peaks around 1983 and takes an overall gradual downward trend towards the end of p3. 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 rise of technological variety supports the idea that many new knowledge sources, mostly external to the existing knowledge base of the industry, are added to the sector. New nodes are added to the structure of the knowledge network, while at the same time the distribution among different domains becomes more equal in terms of the size of innovative activities. This is similar to what Krafft et al. (2009 & 2011) call a *random search* period when companies try many new knowledge pieces that might show some potential for the future of the industry. Major technical fields of the industry are not established yet and large trial and error activities might be experienced. Since companies are bringing new and dissimilar knowledge sources together; they are also taking considerable risks. However, the historical evidence shows that they were willing and also able to take these risks due to the high oil prices of that period and a special political economy environment which supported these big technical jumps (chapter 4). In other words, the search strategies of innovators are dominated by *explorative* activities, as the industry is experiencing a new knowledge discontinuity. The new paradigm has not emerged yet and the trajectory of technical change is still not clear for the participants (Dosi, 1982).

In contrast to breadth complexity, the trend of systemic complexity over most of p1 takes a downward trend. As suggested by Saviotti (2011), it could be explained by higher rate of creation of new nodes, compared to new links between new and existing nodes. 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. The high technical risks involved in new knowledge domains also may prevent innovators from exploring possible complementarities and productive links, before emergence of a relatively clear picture of the trajectory and potential of the new technologies. 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 technological variety or breadth complexity of the knowledge base, while reduce its connectivity and total level of systemic complexity.

As predicted by the knowledge network theory, the situation began to change when the directions of both breadth and systemic complexity reversed in early p2 with a few years delay for systemic complexity. Technological variety took a downward trend in about 1983, followed by rising measure of connectivity of the knowledge network began in 1987. This could be explained by the diffusion and establishment of new technological fields explored in p1, when the rate of creation of new links overtakes the rate of emergence of new nodes. It does not mean that the emergence of new technological domains is stopped, but their relative size became marginal compared to the established technological fields. As a result, the power of the new nodes to reshape the overall structure of the knowledge network was limited.

By the end of p1 and during p2, the most promising fields which involve the highest technological opportunities gradually become known to industry participants. According to Krafft et al. (2009, 2011), we could say that search strategies gradually become *organized* rather than being *random*. The *explorative* behaviours are gradually replaced by *exploitative* strategies applied in the most productive technological areas. This change in strategic behaviour is reflected in the decreasing trend of total variety over p2 which also continues during p3. We see that innovators increasingly innovate more *within* certain technological classes which proved promising and fruitful, instead of spreading their R&D investment across many fields. This interpretation is based on decreasing total variety which reflects increasing concentration and unequal distribution of innovative activities within different technological fields.

Now, it is worth looking at the changing combination of related and unrelated variety in total variety before analyzing the reversed trend of systemic complexity after early p2. In fact, deep understanding of the change in pattern of nodes could pave the way to explain why the pattern of connectivity of the knowledge base reversed. As is evident from figure 5.1 (b), unrelated variety is always larger than related variety and its value is the main determinant of total variety. As a result, the overall pattern of unrelated variety is the main determinant of total variety, increasing during p1 and decreasing after early p2. The prolonged dominance of unrelated variety could be the reflection of highly diverse range of fields with far cognitive distances forming the knowledge base of the sector. The description of the knowledge base of the sector in chapter 4 made it clear how different disciplines from chemistry to mechanical engineering, marine engineering, electronics, telecommunication, etc. are applied in upstream projects. As a result, the *coherence* of the knowledge base in this sector seems less than in sectors like biotechnology, telecommunications and electronics which are formed of relatively more homogeneous pieces of knowledge (Krafft et al. 2009). This could be deduced from the much larger share of related variety in these sectors, compared to upstream petroleum industry with exclusive dominance of related variety.

However, the increasing trend of related variety combined with decreasing unrelated variety after early p2 illustrates that *coherence* has increased over p2 and p3. The analysis of the relative trend of related variety, compared to unrelated variety supports the previous finding that the nature of search strategies over p2 and p3 is more focused and concentrated. In other words, although technological differentiations happen, they are more around and in the vicinity of particular core technologies of the sector which identify as key technologies for the operation of upstream projects. This is reflected in the rising trend of related variety after early p2. It means that the future technological trajectory of the sector has become clearer; therefore innovators seem more confident with respect to general domains of investment for innovation. This situation could have important implications for systemic complexity, because innovators could exploit the complementarities and linkages between established technological domains.

As explained before, systemic complexity matters where strong complementarities are discovered. This is why recent accounts in the theory of knowledge tend to describe it as a ‘co-relational’ entity (Saviotti, 2004, 2007) where different concepts create knowledge if joined together. Therefore, generation of new knowledge in these conditions requires full understanding of the interdependencies and access to a divergent range of complementary pieces. 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 (depth complexity) or simple addition of new technical domains to existing ones (breadth complexity), but through interactions and recombinations between existing and new technologies. These systemic interactions create a new kind of complexity where simple analysis of breadth and depth is inadequate to capture its pattern.

Systemic complexity is considered low when the knowledge base is relatively divisible and decomposable into pieces, and interdependencies are not well defined. In contrast, systemic complexity is considered high when the relationships between different technologies are relatively strong and stable. The interdependencies are defined and synergies and complementarities between technologies are discovered.

We expect the first situation to be observed more in the early stages of industry life cycle or after a large scale discontinuity. The most fruitful links and interactions have not still been explored and companies are searching to find out how the combination of different knowledge domains could create value. The decline of network connectivity over p1 illustrates a reduction of systemic complexity in this period, resulting from the emergence of new but unconnected technologies.

On the other hand, we expect higher systemic complexity when an industry is in its later stages. When new technologies are established and their complementarities are explored, companies could generate new knowledge through recombination processes. This could be a more productive knowledge generation process, because new knowledge is the outcome of the combination of existing knowledge. As a result of this emergent strong complementariness, the knowledge base of the sector is not easily divisible or decomposable and systemic complexity becomes increasingly high. The rise of knowledge network connectivity after early p2 suggests increasing systemic complexity of upstream petroleum industry in this phase.

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 creates important challenges and implications for catch-up processes. It is by definition more to the advantage of those who possesses the knowledge components, and against those who miss one or more of the critical components. These implications of systemic complexity for latecomers will be analyzed in the next chapters.

5.7. Knowledge based perspective to the industry life cycle

In this section, I combine the dynamics of three dimensions of complexity in order to provide a knowledge based perspective to the industry life cycle. The conventional industry life cycle approach (Abernathy and Utterback, 1978) can by no means explain the dynamics and transformation of the upstream petroleum industry, because of the emergence of systemic knowledge base complexity. In contrast, the knowledge life cycle approach seems very helpful to explain how established traditional industries evolve and transform in the era of knowledge based economy. Not only it is useful to explore the regularities in the evolution and dynamics of industries, this picture is required to examine the broad idea that industrial organization and geographies of innovation are at least partly determined by dynamics of sectoral knowledge bases (Saviotti, 2011). Therefore, this chapter is a prerequisite building block for the next two chapters which address the dynamics of sectoral and geographical patterns of innovation.

Generally speaking, we could recognize two main phases and a transitional phase between them in dynamics of knowledge base. These three phases correspond almost to the three periods of the industry explored in the chapter 4: period 1 from early 1970s to mid-1980s, period 2 from mid-1980s to mid-1990s and period 3 from mid-1990s up to the end of observation. The first and third periods are the main periods, because the dynamics of all three dimensions of complexity present a clear, though different trend. Early part of the second period could be defined as the transitional period where the broad trends in all three dimensions seem to be changing.

The first period is when industry was at the stage of new birth preparing itself for a new geopolitical and geographical expansion. Technological innovation was seen as a key to diversify supply sources. High oil prices funded new knowledge generation processes in the sector, creating an emergence knowledge base discontinuity. In this period, the knowledge base of the industry is mainly developed through *exploration* of new technological fields broadening the scope of the knowledge base of the sector. This process is clearly reflected in increasing unrelated variety, illustrating the move towards higher breadth complexity in the knowledge base. In contrast, systemic complexity is decreasing, because links and relationships between new and old technological fields are formed at a lower rate of emergence of new technological areas. Using knowledge network terminology, formation of new ties lags the formation of new nodes leading to lower systemic complexity and connectivity of the knowledge base. This is clearly reflected in decreasing weighted average degree centrality (WACD) of the knowledge base. Nonetheless, the depth complexity of the sector keeps rising, because the size of innovation in existing fields is larger than innovation in new technological areas.

During the early second period, a transition happened which consequently led to the third period when the trends of breadth and systemic complexity reversed. Breadth complexity took a downward trend, as reflected in decreasing total and unrelated variety. This is because the most promising technological areas have been explored, and technological differentiations have mainly happened around these explored promising areas. This is also visible from the rise of related variety over the third period, while total variety is decreasing. The knowledge base of the sector is being developed mainly through *exploitation* and *recombination* of existing technological areas and linkages between them. The outcome is the dominance of systemic complexity in this period, as reflected in rise of the weighted average degree centrality (WADC) of the knowledge network. The rising depth complexity is the only similar dimension to the first period because the share of knowledge generation in existing areas keeps rising.

The famous debate about the distinction between *creative destruction* vs. *creative accumulation* (Pavitt, 1999; Granstrand et al., 1997, Malerba, 2004) seems relevant to the dynamics of knowledge base complexity. The question that stems from this dichotomy is whether the knowledge base of the industry is developed by the mechanism of “creative destruction where the new displaces the old one” or by the mechanism of “creative accumulation” where the new is built on and adds to the old (Pavitt, 1999, p. 183). In other words, the question is whether new technologies are ‘competence destroying’ of dominant organizations which facilitates the entrance of newcomers, or ‘competence enhancing’ reinforcing the role of existing big companies because of their access to the existing accumulated knowledge. The question is whether this dichotomy could describe the dynamics of the knowledge base of the upstream petroleum industry; or whether the three-dimensional perspective could provide a more articulated and subtle description.

What is clear from the dynamics of depth complexity at the level of the upstream petroleum industry is that knowledge ‘destruction’ is always marginal and decreasing, while ‘accumulation’ is pervasive and increasing. In other words, there are very few technological fields which are dropped while the lion’s and increasing share of knowledge generation processes at sectoral level occurs in existing technological classes. In addition, the changes in all-three dimensions are incremental with no rapid destructive periods. However, our evidence supports the idea that what changes from one period to other is better described as a change in the *type* of dominant accumulative processes. The advantage of the three-dimensional perspective to the knowledge base complexity is to reveal how the nature of accumulation process may change over the industry life cycle.

While the dynamics of depth complexity shows that the first and third period could be equally described as ‘creative accumulation’, the diverging dynamics of breadth and systemic complexity illustrate that the nature of accumulation processes in the two periods fundamentally differ. The knowledge base over the first period is mainly developed through the breadth complexity mechanism (broadening) while over the third period the systemic complexity (recombination) mechanism is dominant.

With regard to the *type* of accumulation, the dominance of breadth complexity could create *narrow cumulativeness* over the first period while dominance of systemic complexity over the third period generates *wide cumulativeness*. I do not use high vs. low cumulativeness, because I believe they are *qualitatively* different in their scope, not quantitatively in their scale. When systemic complexity is strong and interactions are intensive between different knowledge domains, introduction of innovation is possible only if all related pieces of knowledge are available. In other words, when systemic complexity is high at sectoral level, a wide range of related and interacting technologies are required to introduce the systemic innovations (Chesbrough and Teece, 1996). This is the direct result of complementarity which leads to *wide cumulativeness* and implies less *decomposability* of the knowledge base (Antonelli, 2003; Yayavaram and Ahuja 2008).

In contrast, when systemic complexity is low, the combination of depth and breadth complexity creates *narrow cumulativeness* and relative high *decomposability*. Accumulation of sophisticated and advanced technology is still necessary but within particular fields. The level of cross fertilization and recombination is low and cumulativeness is defined within specialised fields. As a result, specialization rather than diversification is advantageous for innovators. In this condition, it is easier to introduce stand-alone innovations, because of weaker interdependencies across different technological domains.

The rise of systemic complexity does not mean less innovative performance, but implies innovation largely within well defined trajectories (Dosi, 1982). In fact, the surge of innovation opportunities in the third period could be interpreted as higher productivity and increasing investment returns on innovation. This is because more organized search strategies imply achieving better outcomes, while applying fewer efforts and resources. Therefore, high technological opportunities in the first and the third periods (chapter 4) should be seen as similar outcomes of different creative and search processes. In the first period, the innovation stream is the result of randomly more diffused exploratory processes. In contrast, the innovation stream of the third period is the product of more organised recombinative knowledge generation processes.

Given the dynamics of three-dimensional complexity, the first period may be described as the ‘fluidity’ stage. The structure of the knowledge base is shaky and continuously changing, breadth complexity is increasing and systemic complexity is decreasing. Random search is dominant over organized search and explorative strategies are dominant over exploitation of available knowledge domains. In contrast, the third period could be described as the ‘maturity’ phase, where the structure of the knowledge based is rather stable. Systemic complexity is increasing, breadth complexity is decreasing, organized search is dominant over random search, and firms employ more exploitation than exploration strategies. The second period could be considered as the ‘transition’ phase when the balance of this behaviour gradually changes, perhaps in search for higher productivity in knowledge generation processes.

However, the definition of these three phases according to the knowledge base perspective is very different from conventional industry life cycle (Abernathy and Utterback, 1978). Rather than looking at the horizontal structure of the industry, it looks at the structure of the knowledge base (Saviotti, 2008, 2011). Moreover, there is no assumption about the diminishing rate of innovation when industry matures. In contrast more efficient and productive search and recombination processes may increase the innovative capacity of the sector. In addition, change in the knowledge structure could have important implications for industrial organization, the governance of sectoral knowledge base and the geographical patterns of the innovation, topics which will be discussed in the subsequent chapters.

5.8. Conclusion

The main contribution of this chapter is the provision of a more comprehensive and precise picture of the industry lifecycle in the upstream petroleum industry drawn from a dynamic and three-dimensional perspective to knowledge base complexity. In other words, a ‘knowledge based perspective’ to industry life cycle proved a useful analytical tool to study industrial dynamics in the era of knowledge based economies, and was more relevant than traditional indicators like firm size and number. It is good to see that technological opportunities can be very high in an old and mature industry; and become even greater than in the early stages of the industry. Therefore, the rate of innovation and degree of technological opportunities is only a very partial indicator to distinguish the main phases of industry.

Instead, a patent based description of the dynamics of knowledge base complexity is a more powerful tool to understand industry lifecycle and recognize its main phases. The combination of opportunities and dimensions of complexity is perhaps a better way to describe the dynamics of the knowledge base and follow their implications for industry organization and geography of knowledge and innovation (the topics of two subsequent chapters). This tool proved useful in an industry which is not usually recognized as knowledge intensive and where patents are not the main method for protection of innovation. Therefore, its descriptive power is expected to be higher in other industries. In other words, when an analytical tool works at minimal conditions, we except higher performance when applied in better conditions, i.e. in industries with higher knowledge and patent intensity. This study is an extension of recent research on the lifecycle of knowledge intensive industries (Grebel et al., 2006; Krafft, et al, 2009 & 2011), illustrating the usefulness of the approach even in traditional industries. This suggests that knowledge economy is not crystallized in particular sectors, but is a widespread phenomenon encompassing all sectors of the economy.

Next, the conceptual distinction between the three dimensions of complexity proved not only meaningful but important, as it may have different implications for organization and strategy of innovation and also geography of knowledge. Searching for the main factors behind difficulty of technological catch-up, my broad hypothesis in the beginning of the research was to nominate increasing technological complexity as one of important explanatory factors. However, the concept of complexity for me was rather vague and unclear. The status of the literature also was not satisfying, because of rather vague conception and different interpretations of the concept. I think the suggestion of the three-dimensional perspective of complexity, and more importantly my attempt to measure them over time was an important step forward to address this gap in the literature.

Application of this conceptual frame and methodological approach in the case of upstream petroleum industry also provided interesting new results. In line with recent findings (McGahan and Silverman, 2001; Grebel et al., 2006), my evidence also does not support the idea that mature industries (in the conventional sense) like petroleum industry have necessarily fewer technological opportunities. In fact, we need a more complete definition or a refinement to distinguish different cycles of industries.

My data appears to provide convincing evidence to distinguish between two main cycles of upstream petroleum industry and a transition phase between the two, characterized by the dynamics of complexity and the structure of knowledge base. According to evidence provided, we could label them as ‘fluidity’, ‘transition’ and ‘maturity’ phases. These three phases almost correspond to the main three periods explored in the chapter 4 based on the technological opportunities of the sector. But we need to be careful as the meaning assigned to these phases is very different to the conventional (Abernathy and Utterback, 1978) or even now ‘pre-historic’ perspective. The focus here is not on the horizontal structure of the industry, but on the structure of the ‘knowledge base’.

As analysis of the dynamics of knowledge base complexity shows, the first period can be described as the period of dominance of breadth complexity where companies follow *random search* and *exploration* strategies. The knowledge structure is relatively shaky and changing. These features imply *narrow cumulativeness* for this period. New fields are continuously added to the knowledge base of the sector, but cross fertilizations and linkages lag and are limited. In contrast, the third period is best described as the period of increasing systemic complexity, where recombination and cross-fertilization within defined trajectories become dominant. Firms tend to follow more organized search and exploitation strategies. The aim is to benefit from knowledge complementarities and introduce systemic innovations. The result is a relatively stable knowledge structure and *wide cumulativeness* which stem from complementarities and cross fertilizations. The second period is the phase of transition between these two different periods.

In summary, the first hypothesis (H1) of this thesis that upstream petroleum industry has moved towards technological complexity is empirically supported. However a more subtle and articulated meaning of complexity emerged in this study. We found that the dominant type of complexity in different periods may change. In upstream petroleum industry, depth complexity is shown as a pervasive aspect of complexity which often increases over time. Breadth complexity rises in the early phases then the last period has increasing systemic complexity.

The next chapters analyze the sectoral, organizational and geographical dynamics of innovation associated with dynamics of knowledge base complexity. From both an academic and policy perceptive, it is important to explore how firms and companies respond or adjust their behaviour when facing complexity. Also, the implications of complexity for catch-up processes are of particular interest. I investigate whether we observe associations between the dynamics of knowledge base complexity and governance of knowledge at sectoral (Hypothesis 2) and organisational level (Hypothesis 3) in the next chapter. I also explore its implication for international geography of innovation (Hypothesis 4) in the chapter 7.

6. Chapter 6: Governance of knowledge base complexity

6.1. Introduction

The central aim of this chapter is to understand the mechanisms by which economic agents manage and coordinate the dynamics of knowledge base complexity. The current literature often answers this question without distinguishing between different dimensions of knowledge base complexity. This is one reason why different authors come to different conclusions about the appropriate governance systems for complex knowledge bases. Some suggest emergence of more decentralized governance systems as an organisational response to complexity (for example Ernst, 2005a & 2005b). Others propose more centralized and vertically integrated structures are a more appropriate system for the governance of complexity (for example Pavitt, 1999). Although confusing, those views are not necessarily contradictory, because they concern different *dimensions* of complexity without explicit distinction. Looking at the upstream petroleum industry, I show that the three-dimensional perspective to knowledge base complexity helps to explain the dynamics of governance system.

The relationship between dynamics of knowledge base complexity and appropriate governance system will be examined with reference to two complementary analytical frames. The first frame formulates this relationship in terms of the association between technological regimes and sectoral (Schumpeterian) patterns of innovation, extensively described in chapter 3. This line of research is pushed further in two respects. First, we extend the concept of knowledge base complexity using the three-dimensional perspective. Second, we extend current quantitative econometric studies of the relationship between technological regimes and sectoral patterns of innovation to an inter-temporal design. This extension helps us to examine empirically the *dynamic* relationship between technological regimes and sectoral patterns of innovation which are often analyzed in a static perspective. This approach paves the way to explain transformations of sectoral innovation systems. Based on this frame, we argue in section 6.4 that a change in dominant type of knowledge base complexity from breadth to systemic type is an important driver of transformation of upstream petroleum industry from Schumpeter I to II mode.

The second type of framing, based on distinction between the roles of different organizations in the innovation networks, provides deeper insights compared to the first. I call this strand a *functional* approach, because it considers the role of different actors in the innovation processes, analyzing the different *functions* they serve. The weakness of the first type of framing is its rather implicit homogeneous view of all innovators. It implicitly assumes the similarity of responses of all innovators to an emergent complexity. As a result, it neglects the possibility of operation of different type of agents dealing with complexity in a division of labour where they can serve different functions in the innovation processes. Such an approach is not able to capture possible changes in the role of different actors operating in the system of innovation as complementary and distinctive agents.

The advantage of the second framing is that it disaggregates the data to distinguish the behaviours of various types of agents and their changes over time. As a result, it enables us to see how different agents *collectively* and in relationship with each other manage and coordinate the changing nature of knowledge base complexity. The main contribution to the existing literature is the illustration of the emergence of new systems integrators (Davies, 2005) in the innovations system. These are integrated services companies, that play an important role in the governance of emerged systemic complexity. We argue that the rise of systemic complexity in the knowledge base of upstream petroleum industry has been an important determinant of transformation of certain service companies towards new systems integrators of the sector. This deep understanding of micro processes involved in governance of complexity paves the way for the analysis of the role of geography in managing complexity and catch-up processes, the issue which will be addressed in the next chapter.

This chapter is organized as follows. Section 6.2 briefly introduces the background literature and explains how knowledge base complexity could shape the governance system of knowledge. This issue can be formulated within two analytical frames. The first is the Schumpeterian approach, where the relationship between technological regimes and Schumpeterian patterns of innovation is analyzed. Because this strand of research is extensively discussed in chapter 3, I do not review it here. I focus on the *functional* strand of research where functions of different agents in organizational arrangements in dealing with complexity are examined.

Building on this functional literature and the Schumpeterian tradition introduced in the chapter 3, two hypotheses are formulated in section 6.3. They articulate the association of the dynamics of knowledge governance system and dynamics of knowledge base complexity. Section 6.4 examines the first hypothesis, arguing that increasing systemic complexity can shift the sector from Schumpeter I to II. Section 6.5 examines the second hypothesis, arguing that *new* systems integrators are essential for the governance of increasing systemic complexity. We explore the evolving role of systems integrators involved in the governance of systemic complexity. The last section combines the findings and concludes.

6.2. Governance of complex knowledge in the literature

The appropriate system of governance of complexity in the knowledge base has been the subject of hot academic debates. In addition to the Schumpeterian tradition which analyzes the role of knowledge base complexity as one of the elements of technological regimes in shaping sectoral patterns of innovation, other strands of innovation studies have also addressed this issue. We call this second strand a *functional* approach, because the function of different organizational arrangements in dealing with complexity is taken into account. As the Schumpeterian approach is discussed in chapter 3, I only review the functional approach in this chapter.

Three typical organizational forms for the governance of knowledge can be found in the literature. First, vertically integrated firms which tend to generate and coordinate the knowledge base through hierarchy and systems of command. Second, vertically disintegrated and modular organizations which tend to manage the knowledge base through market based transactions. Finally, networks which combine some features of both in a hybrid structure based on partnerships and collaborations (Brusoni and Prencipe 2001b; Antonelli, 2003; Patrucco, 2011).

The important role of vertically integrated firms in generation and management of new knowledge is highlighted in the seminal works of Penrose (1959) and Chandler (1977).

They explain the logic of economy of scale and scope in the expansion of modern organizations and the role of R&D departments in the production of new knowledge. Most empirical support for this idea came from American companies in the first half of the twenty first century, where oil companies were cited as an illustrating example. In addition, Teece (1984) argued that vertical integration is more efficient in the case of *systemic innovations* where change in one part often involves change in other parts of the system. He explained that markets are often unable to coordinate complementarities because of their weakness in settling the conflicts embedded in the nature of systemic innovations. With particular attention to the American oil industry, Teece (1976) argued against divesture of oil companies, because of its damaging impact on innovation processes.

Relying on a more recent set of evidence based on Simons' (1962) view on complex systems, the modularity literature puts forward a different and rather contradictory argument. The central claim is that when systems become too complex and interactions between different elements are dense, coordination through integrated structures is almost impossible. Under these conditions, modular organizations which operate based on market mechanism are more efficient to coordinate and manage this excessive complexity (Sanchez and Mahoney, 1996). This is because in modular designs, complex systems are broken up into a number of relatively independent modules which interact on a weak basis through standardized interfaces (Baldwin Clark, 2000; Langlois, 2002).

According to the modularity perspective, increasing complexity of products and production processes in more recent times has pushed companies to outsource some functions and move towards higher levels of specialisation (Langlois, 2003). This is because not every individual company can carry all the knowledge required in an industry. In addition, significant gains can be harvested from this modularization as predicted by Adam Smith (1776), because of a finer vertical division of labour leading to specialization and higher productivity (Chesbrough and Kusunoki, 1999). Moreover, emergence of *markets for technology* (Arora. and Gambardella, 1994) facilitated by intellectual property regimes and diffusion of ICT, has reinforced a dis-integration and decentralization trend. Langlois (2003) has described this long term trend as the *vanishing hand* or the return of the Smithian (1776) invisible hand, against Chandlerian (1977) visible hand which temporarily emerged in early twenties century.

Observation of multi-technology corporations (Granstrand et al., 1997) and *complex products and systems* (CoPS) sectors (Prencipe, 2005 &2 006) raised a number of criticisms to this broad modularity approach. This approach, at least in its strong form, pays little attention to the serious *limits* of modularity (Ernst, 2005a) and specialization (Brusoni, 2005; Cacciatori et al., 2005). Knowledge is not like information which is easily decomposable. In contrast and in line with endogenous complexity and evolutionary approach, knowledge should be seen as a system and outcome of a recombination process. As a result, it is not easily decomposable to different modules to be recomposed easily in markets through a simple price mechanism (Arrow, 1969). This is why some argue that the idea of virtual company is not applicable in complex sectors (Paoli and Prencipe, 1999), although it may hold in other modular sectors.

One aim of this revisionist approach (Ernst, 2005) is to explain the emergence of alternative governance structures. A modularly approach on its own is unable to explain the existence of large and technologically diversified companies operating side by side with specialized firms in hybrid structures. When markets are not efficient, close cooperation in hybrid structures may work better. Networks have therefore become the subject of a number of studies as environments in which both big multi-technology and smaller specialized companies cooperate and collaborate to generate and coordinate complex knowledge. There is increasing consensus among scholars that networks include a variety of hybrid structures which can combine the advantages of markets and hierarchies at the same time (Brusoni and Prencipe 2001a & 2001b; Antonelli, 2003; Consoli and Patrucco, 2011).

Elaborating on contrasting evidence, scholars have tried to explain why decentralization in governance of knowledge is not observed in some sectors, as predicted by the modularity literature. Attempts have been made to understand the emergence of a variety of inter-organizational hybrid arrangements. It has been argued that division of knowledge does not necessarily follow the division of labour. In other words, there are many occasions where "firms know more than they make" and knowledge boundaries go well beyond production boundaries (Brusoni et al., 2001). Those companies known as *systems integrat*ors may outsource parts of production activities, particularly in complex products, without necessarily outsourcing the correspondent knowledge domain. In simple words, “there is no one-to-one mapping between product, organisational and knowledge modularity” (Acha and Brusoni, 2008, p. 45). In order to coordinate changes in supply chain and learn about new technologies, systems integrators often develop and maintain technological capabilities in a variety of domains. Achieving dynamic efficiency pushes them to hold distributed competences in various knowledge domains rather than being technologically specialized with distinctive competences. This function explains why “multi-technology” corporations emerge and diversify their technological capabilities (Grandstand et al., 1997).

Moreover, distributed capabilities allow systems integrators to design and continuously revise the template by which complex tasks are decomposed and outsourced to other partners. Without enough knowledge about the latest innovations in different modules, systems integrators are not able to update a template which composes efficiently at design level what is decomposed at production level (Acha and Brusoni, 2008). The template refers to the *architectural knowledge* they have about overall working of the system (Henderson, 1996). This template is not something given, but is an interpretative framework shaped by distributed knowledge through which interdependencies are defined and integrity is maintained. This interpretive framework defines the point of salience or important elements according to which the outsourcing scheme is shaped (Acha, 2003). This capability grants a unique role to system integrators in the innovation network.

The concept of *loosely coupled networks* was proposed in order to clarify some ambiguities in the debate about appropriate forms of organizing technological knowledge in complex systems. Loosely coupled networks are characterised as hybrid combinations between markets and hierarchies, because they express two key features at the same time. First, the ability to master and generate an increasingly diverse range of specialized knowledge in order to keep novelty in the system. This capability is called ‘distinctiveness’. Second, the capacity to coordinate learning and integrate the dispersed bodies of specialized knowledge among different organizations through a coherent governance system. This is called ‘responsiveness’ (Brusoni and Prencipe, 2001b).

On the one hand, increasing division of labour implies rapid expansion in the number of specialized bodies of knowledge needed to be combined in the final product. On the other, greater integration and coordination capacity is required to keep the network coherent and guarantee alignment between various specialized knowledge flows. While the first task is more a function of specialised entities in the network, the second is more the responsibility of systems integrators. Greater specialization and division of labour among specialized firms requires a broadening of the knowledge base of the systems integrators. This allows them to understand external sources of knowledge, manage the integration of outscored components, and coordinate the collective and distributed innovation processes.

Loosely coupled networks should not be seen as a fixed pre-defined structure but as a range of possibilities between two extremes of markets and hierarchies. A number of factors define which structure is more appropriate. The degree of coupling could vary depending on the predictability of interdependencies and rate of change in component technologies (Brusoni et al., 2001). However, as the semiconductor industrial sector shows, there is not necessarily one optimal form of governance and it may also depend on the firm’s history and strategy (Linden and Somaya, 2003). Even the same company may employ *mixed modes* of governance in order to leverage a comparative advantage (Jacobides, 2008), as shown in the case of the mortgage banking industry (Jacobides and Hitt, 2005).

Dynamic analysis of modes of governance has shown that industries can swing between integration and disintegration, as the outcome of dynamic co-evolution between firm capabilities, learning processes and transaction costs (Jacobides and Winter, 2005; Rosiello 2007; Jacobides, 2008; Parmigiani and Mitchell, 2009). Some of these studies also touch upon the changing role of the knowledge base in triggering both disintegration and re-integration processes (Cacciatori and Jacobides, 2005; Brusoni and Prencipe, 2006; Acha and Brusoni, 2008). However, they are yet to provide a full understanding of the nature of the knowledge base and its implications for the way in which- firms organize knowledge generation, sharing and integration processes. This field is becoming a very important research area where concrete insights are increasingly demanded (Brusoni et al., 2009).

6.3. Hypotheses

Building on a combination of these *functional* studies and the Schumpeterian approach reviewed in the chapter 3, we examine how dynamics of knowledge base complexity can shape the governance of knowledge in the upstream petroleum industry. The central aim of this chapter is to answer the second research question of this PhD thesis:

Q2: How is the governance system of sectoral knowledge base adapted to the dynamics of technological complexity? And how have different firms responded or adjusted to the dynamics of technological complexity?

This question will be answered using the two analytical frames mentioned above. These generate two different, yet related and complementary hypotheses.

Under the first frame based on Schumpeterian approach, we develop our second thesis hypothesis (H2) which describes the association between knowledge base complexity and Schumpeterian patterns of innovation. This largely follows the Schumpeterian logic described in chapter 3.

Under the second frame we develop our third hypothesis (H3) to describe the relationship between knowledge base complexity and the role of different players (specialists vs. systems integrators) in the innovation network. This is largely based on the *functional* literature discussed in this chapter.

I believe that these two frames provide complementary answers to the research question, considering different aspects of governance of knowledge. The Schumpeterian approach is most concerned with the relative role of firm size and experience in the knowledge generation process. As a result, it analyzes the role of small vs. big and new vs. incumbent companies in the innovation processes of different sectors. On the other hand, the functional approach is most concerned with the role of different organizations in different organizational arrangements with respect to innovation and knowledge generation process. This is why it considers the role of specialist vs. diversified and systems integrators in innovation networks and is concerned with the advantages and disadvantages of markets vs. hierarchies in dealing with knowledge base complexity.

Having theoretical insights from both framings and the empirical assessment of dynamics of knowledge base complexity in upstream petroleum industry from chapter 5 we propose two hypotheses. We observed that over p1, breadth complexity in the knowledge base of the sector is increasing while its connectivity and systemic complexity is decreasing (period 1). In this phase, the sector is mostly in its random search period and exploration strategy is dominant. Because the structure of the knowledge base is changing and is not yet established, the cognitive barriers to entry are relatively low, and cumulativeness is low and narrow (See section 5.6 and 5.7).

The complementarities between new and old knowledge domains have not been fully explored and recombination process and linkages are not effective. In terms of knowledge network, poorly connected nodes emerge. As a result, access to a wide range of complementary knowledge is not necessary for innovation processes in this stage. Therefore we expect an increasing role for small and new companies relative to the role of big and established companies in the organization of innovation processes. In short, we expect the sector to move towards a Schumpeter Mark I mode. Since the level of systemic interdependencies and complementarities is low, we expect many companies to leverage the gains and benefits of finer division of labour and employ a technological specialization strategy.

In contrast, we observed that after early part of period 2 (p2) and over p3, systemic complexity expresses a relatively sharp rising trend while breadth complexly gradually declines. As explained in chapter 5, when systemic complexity increases, the sector moves towards a more organized search period and exploitative strategies are pervasive. Core technological domains are realized, technological trajectories are relatively clear and most of the productive complementarities and technical interdependencies are explored by key players. Big companies therefore can gain from economy of scale and scope in knowledge generation and utilization processes. Cognitive barriers for small specialised companies are relatively higher, because successful innovation involves combination and recombination of various range of knowledge domains.

In addition, increasing returns stemming from complementarities and fungeability of knowledge (Antonelli, 2003) favours big technologically diversified companies. As a result of the wider cumulativeness and higher appropriability mechanisms which emerge, big companies manage to benefit from cross-fertilization between different knowledge domains and their wide range of applications. The entry barriers for new companies will be higher and growth opportunities for small ones are limited. As a result, it is reasonable to expect that the sector becomes similar to or moves towards a Schumpeter Mark II mode. Also, systemic interdependencies imply that at least some companies as systems integrators broaden their technological boundaries in order to mediate the dynamics of knowledge flows in the network and coordinate technical changes in the sector.

Of course, as the loose network perspective (previous section) suggests, alongside systems integrators, we may still, and actually should have, some specialists who contribute to both the breadth (bringing new knowledge domains) and depth (deepening the current specialized knowledge domains) complexity of the sector. However, as theory suggests, it is the responsibility more of systems integrators to manage excessive systemic complexity, mediating the technical interdependencies and system wide interactions. Accordingly, the two hypotheses based on two analytical frames are formulated, as follows:

According to the Schumpeterian analytical frame:

Hypothesis 2: we expect the sector to move towards Schumpeter Mark I over p1 when breadth complexity is increasing and systemic complexity is decreasing. We also expect a shift towards Schumpeter Mark II after early p2 when systemic complexity is increasing and breadth complexity declines.

According to the functional analytical frame:

Hypothesis 3: we expect most of the agents to follow a technological specialization strategy over p1 when breadth complexity is increasing and systemic complexity is decreasing. We also expect some of the agents which become system integrators to shift towards a technological diversification strategy after early p2 when systemic complexity is increasing and breadth complexity declines.

As figure 5.1 shows, the dynamics of complexity expresses two main phases and a turning point in early p2. This is why the two hypotheses are framed according to ‘before and after’ the early part of period 2 (p2). Thus, the second half of p2 and p3 show similar properties after the turning point observed in early p2. The three phase periodization suggested in chapter 4 was based on the dynamics of technological opportunities. However, the dynamics of complexity do not necessarily correspond exactly to the dynamics of opportunities. In our subsequent analysis we examine the dynamics of the sector in two main phases.

The next two sections focus on operationalization and empirical examination of these two hypotheses. We also provide a discussion about the new theoretical insights which can be drawn from the empirical observations. In order to distinguish the governance of knowledge under a Schumpeterian approach, we use the term ‘sectoral patterns of innovation’ in line with the literature discussed in the chapter 3. In parallel, we reserve the term ‘organizational patterns of innovation’ to refer to the governance of knowledge within functional approach in the second framing, reflecting the different roles or functions of different organizations in the innovation processes.

6.4. Sectoral patterns of innovation

In this section, we analyze the sectoral pattern of innovation as one aspect of the dynamics of the knowledge governance system. This framework is concerned with the relative role of big vs. small, and new vs. incumbent innovators in the innovation process. Following established literature (Malerba and Orsenigo, 1996; 1997; Breschi et al., 2000), we use a set of variables to examine whether the sector is moving towards Schumpeter I over p1 and shifts towards Schumpeter II after early p2, as predicted by the hypothesis 2. Although we use a similar set of variables, there is a fundamental difference between this study and previous research, as explained in the chapter 3. These variables are normally used to distinguish different patterns of innovation in inter-sectoral studies. However, I employ them in an inter-temporal mode of analysis to explore the shift of sectoral patterns of innovation over time. This novel application is a step forward for extension of quantitative methods to the analysis of transformations of sectoral innovation systems which is a relatively neglected research area.

Four indicators selected for the analysis of the dynamics of sectoral patterns of innovation are based on previous studies (Malerba and Orsenigo, 1996; 1997; Breschi et al., 2000). They are: concentration of innovative activities (C); the number of innovative firms (F); share of new entries (NE) to the innovation system in terms of the proportion of patents registered by new innovators; and, stability of the ranking of innovative firms (STR).

Although the variables of this inter-temporal research are similar to previous cross-sectoral studies, their operational correspondence with archetypical Schumpeterian patterns of innovation is interpreted differently. Due to dynamic nature of the analysis, we are interested more in the *trends* of variables, rather than their relative values in cross-sectional designs. In other words, interpretation is performed based on relative change of the variables over time.

Accordingly, positive or negative changes in these four variables will show toward which archetypical Schumpeterian patterns of innovation the industry is moving. I ask whether it is becoming closer to a typical Mark I or becoming similar to a typical Mark II type. Table 6.1 summarizes the operational account of archetypical Schumpeterian patterns of innovation in a dynamic perspective and the direction of the variables we expect to observe in each typical mode. The Schumpeter Mark I sector is relatively open to the entrance of new or small firms. Therefore, we expect that over time, new firm entry and the number of innovating firms will increase, and as a result the concentration of innovative activities will decrease. This implies the relative low stability of the ranking of innovators, because new or small innovators have the opportunity to challenge the position of top innovators.

Table 6-1 Archetypical Schumpeterian patterns of innovation in dynamic perspective

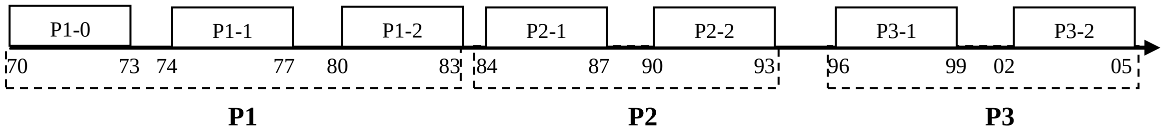
Schumpeterian patterns of innovation	Schumpeter Mark I Widening	Schumpeter Mark II Deepening
Concentration (C)	↓	↑
Number of firms (F)	↑	↓ -
Entry of new firms (NE)	↑	↓
Stability of ranking (STR)	L	H

In contrast, a typical Schumpeter Mark II sector is relatively closed to new or small innovators and works in favour of large innovators. Therefore, we expect to observe a decreasing trend in the contribution of new firms. The number of firms may be relatively stable (as shown in table 6.1) or even decrease over time, depending on the size of exiting firms. This implies a rise in concentration of innovative activities in the sector which leads to relative stability particularly among big innovators.

To explore in the different periods, the Schumpeterian patterns of innovation, we need to measure the changes over time of these four variables. Comparison of the observed trends with table 6.1 reveals the dominant pattern. We stick to the three main periods explored in the chapter 4. In order to smooth the trends and ignore the short term fluctuations, the measures are drawn from data collapsed within 4 years of the beginning and the end of the main periods.

The first main period (p1: 1970-83) is formed of three sub periods (p1-0: 1970-73; p1-1: 1974-1977; p1-2: 1980-83). The second main period (p2: 1984-1993) is formed of two sub-periods (p2-1: 1984-1987; p2-2: 1990-93). The third main period (p3: 1996-2005) is formed of two sub periods (p3-1: 1996-99; p3-2: 2002-2005). 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 (figure 6.1).

Figure 6-1 Periodization of the analysis



Using this periodization helps to control for the impact of change in technological opportunities on the selected variables, and therefore unravels the role of knowledge base complexity in the dynamics of sectoral patterns of innovation. The advantage of this sub periodization is that we can trace the dynamics of sectoral patterns of innovation over the main periods (p1, p2 and p3) and compare them.

In the next sections, I present and explain the dynamics of four indicators of Schumpeterian patterns of individually. In section 6.3.4, I combine the results to explore whether the dominant Schumpeterian patterns of innovation have changed over time. In addition, I discuss how the observed dynamics in Schumpeterian patterns could be associated with dynamics of knowledge base complexity and change in technological regimes. The empirical findings support the second hypothesis of this research suggesting an association change in the dominant type of knowledge base complexity and Schumpeterian patterns of innovation from mode I to mode II. In addition, we suggest that positive (or negative) change in technological opportunities tend to strengthen (or weaken) the existing Schumpeterian pattern without altering it. Accordingly, a theoretical fretwork is suggested to explain the dynamics of Schumpeterian pattern of innovation according to the combination of knowledge base complexity and technological regimes.

6.4.1. Concentration and number of innovators

The top part of the figure 6.2 shows the trend of concentration over time for different size groups using a corrected version of Herfindahl index of concentration. The advantage of this corrected version is that it controls for small sample bias (Hall, 2000; Corrocher et al., 2007). I repeated the indicator for different subset of companies defined by innovation size (for N<40, N<100, N>40, N>100 and All companies: N is firms' total innovation size) to check the robustness of the results in different size groups. The top left side of the figure (a) displays C for large innovation size group and top right side of the figure (b) shows it for smaller sizes. Regardless of the size categories, all of the indicators present an overall U shape pattern reaching their lowest points in p1-2 or p2-1. The two lowest figures show the number of innovative firms over time, by innovation size category.

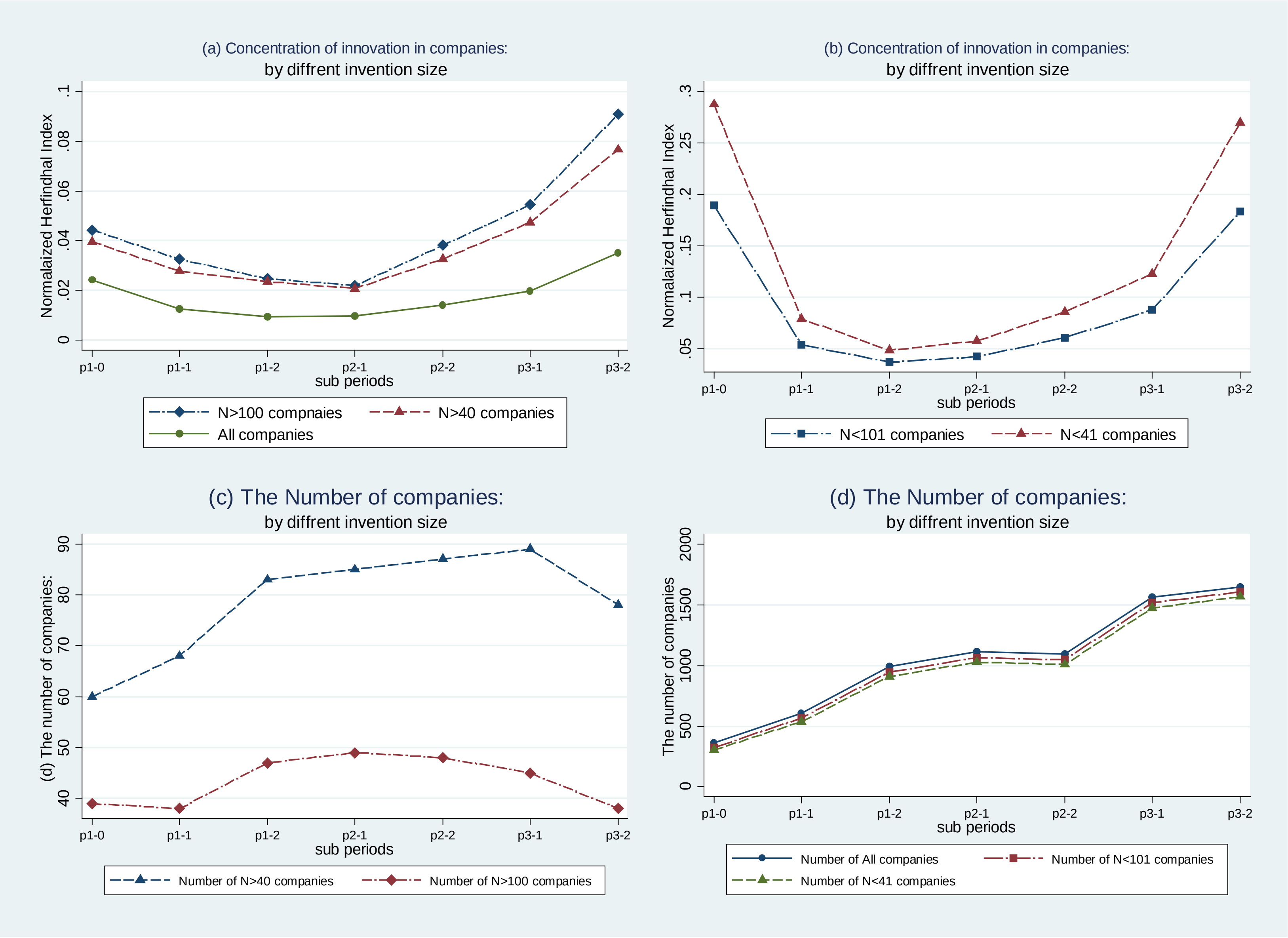
According to these figures concentration (C) decreases in p1 (and even up to p2-1 for larger groups). In parallel, firm numbers (F) increase in almost all size categories. High technological opportunities driven by high oil prices seem to have worked as a powerful incentive for smaller firms to catch-up with major innovators. The increasing number of innovative companies in all groups also confirms the key role of new innovators in p1. Their considerable share in innovative activities challenged the relative position of big existing innovators pushing down the C index. Another complementary mechanism for the increasing number of firms and decreasing concentration could have been the progressive outsourcing strategy of oil operators to supply and service companies, as explained in chapter 4.

As oil prices collapsed in p2-1 and the declining trend continued in the second period, the upstream petroleum industry was not very rewarding for innovation. Over p2, F slightly decreased and C took a clear upward trend. One reasonable explanation could be the higher vulnerability of some smaller firms, when a continued low opportunity environment would dry up their innovative efforts. Due to the high risk and uncertainty involved in innovative activities, many firms may cut R&D investment in poor market conditions. As we know from chapter 4, the number of patents has a negative trend in p2. Yet increasing concentration of innovative activities, combined with reduction in the number of innovative firms, suggests vulnerability of smaller firms which exit from the system of innovation. In fact p2 is the only period with negative net entry. In addition, a wave of M&A activities, triggered by low oil prices in p2 could be a complementary mechanism responsible for higher concentration. Nonetheless, acceleration of outsourcing strategies by oil operators should have compromised the trend of concentration in p2, which otherwise would be sharper.

The beginning of the third and final period (p3) presents an interesting and puzzling pattern. By the end of p2 and the beginning of p3 a new wave of innovative entry is observable resulting in a sharp rise of F (fig 6.1 d) in all size categories, with the exception of super big innovators (N>100) (fig 6.1 c). This should have been driven by the jump in technological opportunities observed after p2-1 (chapter 4). Although F transforms sharply from a negative trend in p2 to a sharp positive trend in p3, there is no expected corresponding drop in C. In contrast, C continues its upward trend which is reinforced over p3.

This pattern reflects the relative low and weakening share of new entrants in p3, compared to big incumbents (figs 6.1a & b). In addition, the short term jump of F before p3-1 (fig 9.1b) turned into a relatively stable trend in p3, whilst concentration gained momentum.

Figure 6-2 Concentration of innovative activities (a & b) and the number of innovative firms (c & d): by innovation size



These patterns suggest a fundamental difference between p1 and p3. We observe that high opportunity environments in both periods encourage new innovators to enter into the sector - reflected in the rise of F. However C presents opposite trends - decreasing in p1, but increasing in p3. The key question is: what could explain the fact that in p1 new small innovators could benefit from high opportunity conditions and challenge the position of bigger established firms, whilst in p3, established big innovators gain much more than new innovators from expanding innovation. The trend of these two indicators corroborates the hypothesis of a shift in the Schumpeterian pattern of innovation after the early part of p2.

The answer lies in the changing nature of technological regimes, particularly the complexity of the knowledge base. Our analysis in chapter 5 provides convincing evidence that increasing systemic complexity of the knowledge base favours big innovators. Similar arguments have been raised about the other elements of technological regimes such as appropriability and cumulativeness, although complexity is a relatively neglected element. Ceteris paribus, Breschi et al. (2000) explain that high technological opportunities favour a reduction in concentration, because they allow for entry of new innovators. The opposite relationship also holds for low opportunity conditions. Nonetheless, according to several different theoretical models (Nelson and Winter, 1982; Jovanovic and Lach, 1988; Winter, 1984; Dosi et al. 1995), under conditions of high technological appropriability and cumulativeness, high technological opportunity leads to rise of concentration. This is because this combination with technological opportunities creates major difference between big incumbents and small new innovators in terms of innovation rates. On the one hand, high appropriability limits the extent of knowledge spillovers creating relative advantage for big successful innovators. On the other hand, cumulativeness and concentration have a positive relationship, because the ability of existing big innovators to introduce new innovations is higher.

A similar argument holds for systemic complexity where the difference between p1 and p3 can be explained by their underlying technological regimes. While in p1, small innovators could benefit from high opportunities because of low systemic complexity; this is not the case for p3. Systemic complexity in p3 would increase the cognitive barriers to entry for small and newcomer companies. Although there are high technological opportunities driven by recombination processes (as shown in chapter 5), they are mostly available to large technologically diversified companies. This is because they have access to the required knowledge segments as well as integrative and combinational capabilities. Small and new firms may innovate in specialized niche technical areas, but their relative role is lower. Under these conditions big incumbents are at an advantage compared to small and new comers, because they benefit from their investment in innovation processes without serious worries about free riding and large externalities (Breschi et al., 2000). As explained in chapter 4, many M&A activities over p2 and p3 have also been of ‘technology led’ type, driven by technological interdependencies, moving the industry towards higher concentration.

6.4.2. Share of new entry to the system of innovation

This section analyzes the relative chance of new innovators in comparison with incumbents to contribute to the development of the knowledge base of the industry. Table 6.2 shows the number of patents of existing and new firms in each sub-period; and also the new innovators' share of patents (NE) in each sub-period. This is measured for different innovation sizes of firms (with the minimum patent size of 1, 5 and 10), in order to get insights about the role of size for successful entry. The trend of NE is also shown in figure 6.3 for visual presentation.

Table 6-2 New entries to the innovation system: by different innovation size

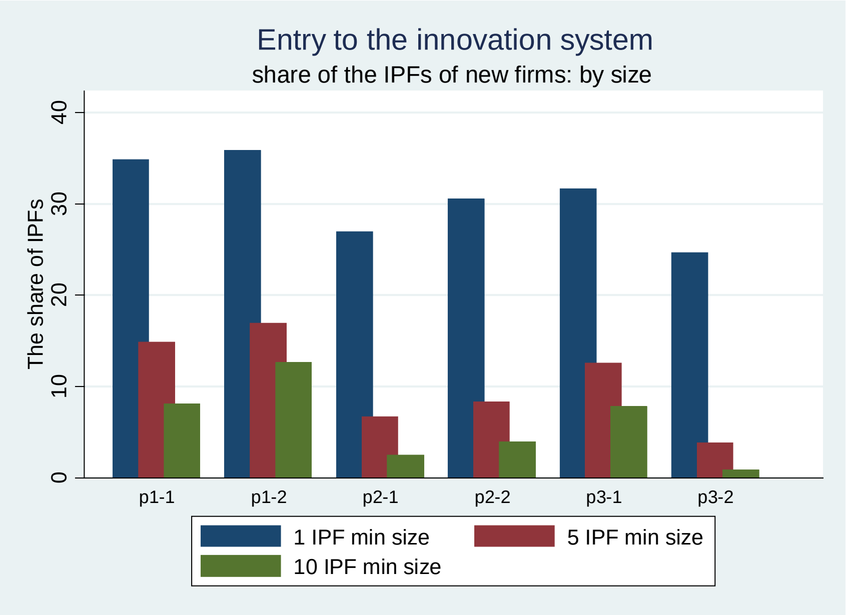
(a) New firms’ share of patents: by size

	1 IPFs min size			5 IPFs min size			10 IPFs min size		
Sub periods	IFPs Existing Innovators	IPFs New Innovators	Share of new entry (NEP)	IFPs Existing Innovators	IPFs New Innovators	Share of new entry (NEP5)	IFPs Existing Innovators	IPFs New Innovators	Share of new entry (NEP10)
p1-1	1297	693	34.82	1272	222	14.86	1222	108	8.12
p1-2	2205	1232	35.85	2166	442	16.95	2062	298	12.63
p2-1	2802	1033	26.94	2714	195	6.70	2588	67	2.52
p2-2	2528	1112	30.55	2459	223	8.31	2348	97	3.97
p3-1	4226	1957	31.65	4127	595	12.60	3952	337	7.86
p3-2	5291	1732	24.66	5089	203	3.84	4853	45	0.92

According to table 6.2, the share of new entry during period 1 (p1) increases from about 34.8 percent to 35.9 confirming a 1% rise in the chance of new innovators. This is considered significant, because the indicator is drawn from the whole population. A test of significance is irrelevant, because no sampling method is applied. The amount of increase is even greater for bigger innovators (about 2% and 4% for 5 and 10 IPFs minimum size), suggesting the increasing possibility of moving up of the hierarchy among larger firms. Overall, the new entry indicators confirm the increasing chance of new innovators over p1 for all size of the firms.

Transition from p1 to p2 is accompanied by about a 10 percent reduction of new entry for all size ranges. It is rather intuitive that the arrival of low opportunity conditions in p2 has worked against new entries, as the expected returns on R&D has reduced. Over p2, when low innovation opportunity conditions are established and companies have adjusted to the external shock, part of this lost contribution of new entrants recovered. This is reflected in the rise of NE for all size innovators. This is rather counter intuitive, because low opportunity conditions do not motivate new innovative entries. We normally expect a fall or stability of new entries.

Figure 6-3 The percentage share of the IPFs by new innovators



According to the historical analysis of chapter 4, the most reasonable explanation is the accelerated outsourcing strategies of operators over this period which created new innovation opportunities for the service sector. In fact in many cases, operators supported the formation of specialized service companies as a result of poor market conditions. A horizontal disintegration strategy was followed to reduce fixed costs and increase specialization, efficiency and responsiveness. This rather long term response of oil operators to the unsuitable economic environment created a new division of labour in which part of the locus of innovation in upstream petroleum industry transferred to new entities. As a result, our evidence tends to attribute the rise of new entries over p2 to the emergence of a *new division of knowledge* in the industry.

The distinction between short term and long term responses of the sectoral innovation system to low opportunity conditions is an interesting finding. The short term response of industry to low opportunities was reduction of new entries. However, the long term response was formation of a new division of knowledge or more precisely new *industry architecture* (Brusoni and Jacobides, et al., 2009). This favoured new entrants and launched a new knowledge dynamic. Transition from the low opportunity conditions of p2 to high opportunity conditions in p3 amplified these new entrants as reflected in the continued rise of NE for all sizes ranges from p2 to p3.

Over p3, we observe a relative reduction of new entrants in all groups, to their lowest levels over the whole period of observation. In contrast to the high opportunity conditions of p1 over which new entries experienced their maximum level, the possibility of new entries over p3 seems to reach to its most limited status. Ceteris paribus, the standard theory of patterns of innovation predicts a positive relationship between opportunities and new entries (Breschi, et al., 2000). It means we expect to observe increasing entry rates in both p1 and p3.

These predictions however are conditional on the nature of technological regimes. For example, high new entry is expected under low cumulativeness conditions when "would-be innovators are not at major disadvantage with respect to incumbent firms" (p.393). Our analysis in chapter 5 suggests that the difference between p1 and p3 in terms of new entries can be attributed to the dynamics of knowledge base complexity. New entrants are at a high disadvantage in p3 compared to p1 because of the change in underlying technological regimes. As explained in chapter 5, the rise of systemic complexity over p3 can involve wider cumulativeness implying higher cognitive barriers to entry. This constrains the exploitation of high technological opportunities by new and small companies in this period.

6.4.3. Stability of ranking of innovative companies

Stability of ranking of innovators is the last indicator of the sectoral pattern of innovation that I examined. I computed the Spearman correlation coefficient of the ranking of patentees. This measure is usually interpreted as an index for the degree of creative accumulation vs. creative destruction at firm level for cross-sectional analysis of different industries (Malerba and Orsenigo, 1995, 1996, 1997). Unfortunately, I could not find robust and consistent patterns in inter-temporal analysis of this indicator. Several types of anomalies were observed which together make this index quite challenging and difficult to interpret. These inconsistent patterns could be the synthetic product of several phenomena such as structural changes (combination of outsourcing and M&A activities) and dynamics of technological regimes which is not possible to disentangle easily. Due to these difficulties I do not include the result of this measure in my further analysis. I think this proxy is not a robust and reliable indicator to capture the degree of creative accumulation vs. creative destruction, when the sector is involved in continued structure changes. This is so at least in inter-temporal analysis, even if not the case in cross-section approach.

6.4.4. Sectoral patterns of innovation and knowledge base complexity

So far, the dynamics of the sectoral pattern of innovation in the upstream petroleum industry are analyzed with respect to three indicators over 3 main periods. Table 6.3 summarizes the changing pattern of these indicators. Also, it shows the observed dominant pattern in each period drawn with reference to typical Schumpeterian model (table 6.1). Arrows specify the magnitude of changes in the indicators over that period, according to the data presented in previous sections. According to these results, p1 could be characterised as strong Mark I, because of a considerable reduction in the concentration, a large increase in the number of firms and the rise of new entrants.

The second period presents a pattern which is more similar to Mark II, although its signals are still weak. Concentration (C) began a slight upward trend and F reduced to some extent, as technological opportunities were relatively low. Although NE shows an upward trend over p2, this can be explained by the accelerated outsourcing of oil operators driven by low oil prices. In the absence of this structural change, we could have observed higher concentration, less number of innovative firms, and downward new entries. This is why I think it is better to label this period as weakly Mark II, putting aside the effect of structural change on new entries. The analysis of knowledge base complexity in chapter 5 also supports the idea that p2 is the beginning of the rise of systemic complexity. As I explained, systemic complexity favours big incumbents and works against small and newcomer firms. This is reflected, although not still very strongly, in the trend of the indicators in p2 which fits with Schumpeter Mark II.

Table 6-3 Dynamics of Schumpeterian patterns of innovation

Periods	**1st period**	**2nd period**	**3rd period**
Schumpeterian pattern of innovation	Strong I	Weak II	Strong II
Concentration (C)	↓↓	↑	↑↑
Number of firms (F)	↑↑	↓	-
Entry of new firms (NE)	↑	↑	↓

The signs of Schumpeter Mark II get considerable strength when technological opportunities increase over p3. Although technological opportunities are high, new entries are reduced and the number of firms stays relatively stable. Most importantly, the upward trend of concentration accelerated. When the three indicators are combined together, the picture looks like a relatively strong Mark II. The high barriers of entry in this period for new small companies and relative advantage of big incumbents is attributable to the systemic complexity of the knowledge base.

The above analysis had two parallel objectives: first to describe the dynamics of sectoral patterns of innovation. I argued that that the upstream petroleum industry presents an interesting dynamic, beginning with a strong Mark I over p1 which gradually weakens and transforms to a weak Mark II over p2. This weak mark II style is reinforced over time, ended up in a pattern resembling a very strong Mark II. The second aim also was to examine whether these dynamics are associated with changes in technological regimes. Dynamics of two particular elements of technological regimes were emphasised: technological opportunities and knowledge base complexity.

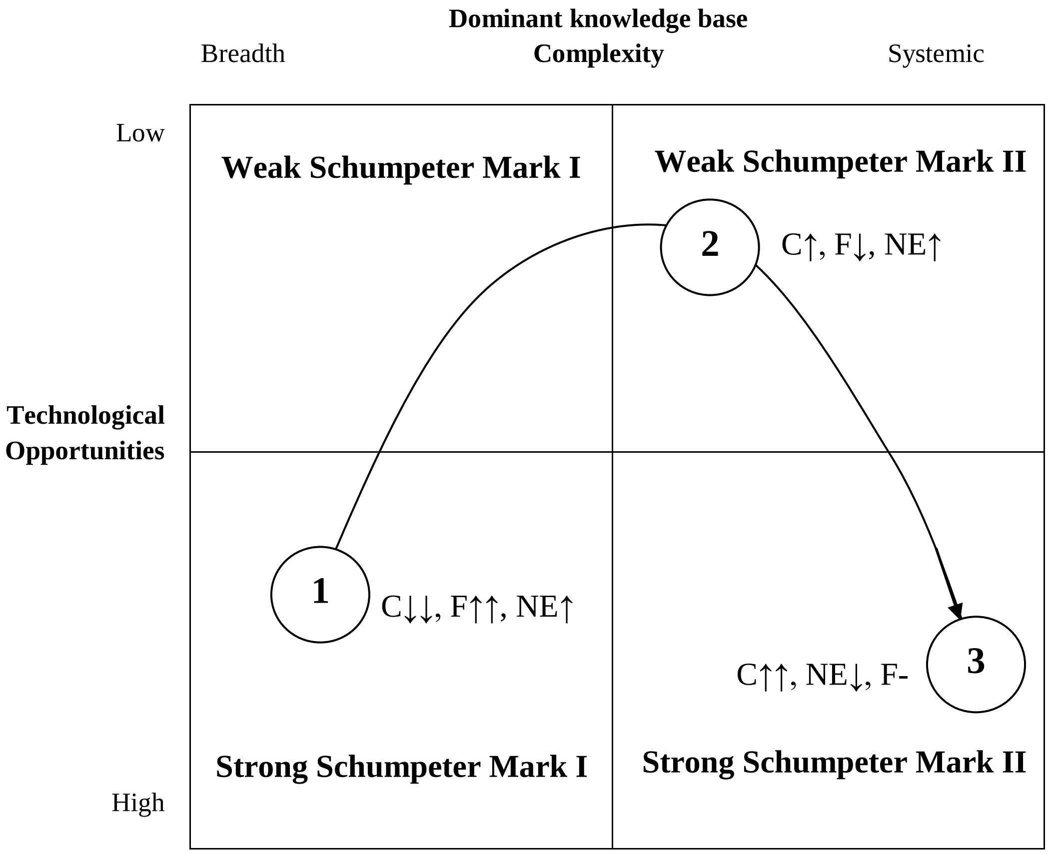
The results suggest that change in technological opportunities tends to associate with the *degree* of change in *existing* patterns of innovation. The existing pattern of innovation is weakened when changing from high to low opportunity (as observed over transition from p1 to p2) and is reinforces when changing from low to high (as observed over transition from p2 to p3). However, this element of technological regime, on its own is unable to explain the shift in *mode* of Schumpeterian pattern of innovation from I to II. This is best understood by looking at the two extremes of p1 and p3, when two quite different patterns of innovation are observable while technological opportunities are high in both periods. If the concept of technological regimes is to convincingly explain the shifts in the *mode* of Schumpeterian pattern, at least one additional element should be taken into account. Our evidence in chapter 5 suggests that knowledge base complexity is a reasonable candidate in the case of the upstream petroleum industry. The results propose the dominance of breadth over p1 is consistent with Schumpeter Mark I. When systemic complexity of the knowledge base increases in early p2, the features of Mark II emerge in the sector. Higher opportunities in p3 reinforce this pattern.

These findings clearly support the second hypothesis of this research. As predicted, the upstream sector seems to move toward Mark I over p1 and shift towards Mark II over p3.

In addition, a novel theoretical framework can be drawn from the results which explain the dynamics of sectoral patterns of innovation according to the combination of technological opportunities and knowledge base complexity. The impact of the combination of these two dimensions of technological regimes on change of *degree* and *mode* of Schumpeterian pattern of innovation is visualized in a 2x2 matrix in figure 6.4. The vertical axis specifies the high vs. low technological opportunities and horizontal axis represents the dominant type of complexity. As I explained in the section 6.3, dominance of breadth vs. systemic complexity could favour the dominance of two different *types* of Schumpeterian pattern of innovation (Mark I on the left and Mark II on the right of the matrix differentiate these two types). Change of technological opportunities tends to weaken or reinforce the *degree* of existing pattern, whether it is

Mark I or II, but not alter its mode. Therefore, the top side represents the weak type and the bottom accommodates the strong one.

Figure 6-4 Technological regimes and Schumpeterian pattern of innovation



The evidence drawn for the upstream petroleum industry supports this novel theoretical framework. The curve in figure 6.4 shows how the upstream petroleum industry has trawled through different sectoral patterns of innovation in different periods. The circles represent the main three periods of p1, p2 and p3 beside which the trend of indicators is shown (according to the table 6.3). The location of each circle in the matrix represents the configuration of two elements of technological regimes shaping sectoral pattern of innovation. This theoretical framework can be empirically examined in other industries experiencing dynamics of technological opportunities and knowledge base complexity. It is a valuable analytical tool for further research in drivers of transformation of sectoral innovation systems.

6.5. Organizational patterns of innovation

Analysis of the evolution of sectoral patterns of innovation in the previous section supports the idea of their association with the nature of knowledge base complexity. Nonetheless, that approach is unable to distinguish between different actors who might play different and changing roles in management and governance of knowledge base complexity. Not all companies in the sector play similar roles in knowledge generation and utilization processes. Some are major knowledge producers. Others may only be users with a limited role in knowledge production processes. Some companies are knowledge specialists, concentrating on knowledge production in very narrow technical areas. Others might be multi-technology corporations creating knowledge in a large number of domains. In fact, knowledge specialization and integration are two sides of the same coin, both of which are required for the development of the knowledge base of an industry (Brusoni and Geuna, 2005). On the one hand, specialization is the process by which economically relevant knowledge is produced. On the other hand, we need to coordinate, integrate and control these distributed specialized knowledge in order to introduce better products and services and improve the production processes (Pavitt, 1998; Loasby, 1999).

Organizational pattern of innovation defines the role of different types of actors in governance of knowledge base complexity. In parallel with the concept of *sectoral pattern of innovation* which focuses on *aggregated* sectoral level dynamics, I define the concept of *organisational patterns of innovation* referring to *disaggregated* dynamics of the role of different types of actors. Our dataset allows us to distinguish between three main types of actors in the top 50 patentees in the sector. These are integrated oil companies (IOCs), integrated service companies (ISCs) and other specialized supply and service companies (SSCs). We explained how their different roles in the industry architecture changed over time in the chapter 4.

In this section, I explore their different and evolving roles in knowledge production activities and innovation processes. The aim is to understand how different agents position themselves when facing the evolution of knowledge base complexity. I analyze their evolving roles in terms of dynamics of size (growth vs. de-growth) and direction (specialization vs. diversification) of knowledge activities. These measures are used to examine the third hypothesis of this PhD formulated in the section 6.3. Before presenting the results of these two variables, the relative size of contribution of different types of companies is analyzed to explore how their relative position has changed over time.

6.5.1. The share of knowledge contribution

Figure 6.4 shows the trend of patenting by the top 50 patentees differentiating the share of different types of companies over time. Part (a) of the figure illustrates that these top 50 patentees together are roughly responsible for more than half of innovations with a relatively smooth share over time. The number of International Patent Families (IPFs) is presented by each type of company (b), their share among all patentees (c) and also among top 50 patentees (d).

There are some important facts in these figures which need consideration. Clearly, IOCs were the dominant innovators of the industry in early 1970s with about 35% of all patents and more than 60% among the 50 patentees. However, their share shows a decreasing trend until 1980 when they show a short term upward trend. This short term upward trend is probably driven by large R&D investments during oil shocks. If absolute trends are also taken into account (fig 6.4 b), it is obvious that the increasing contribution of ISCs is mainly responsible for the long term decline in the share of IOCs. However their deceasing level of innovative activities over p2 has also accelerated this negative trend. With the exception of p2, IOCs present a more or less stable behaviour in other periods in terms of absolute level of innovative activities.

In contrast, the sharp increase of innovative activities by ISCs eroded the share of both IOCs and SSCs in 1990s and 2000s. In fact before 1990s, current ISCs were performing even less than SSCs. According to this data, the distinguishing concept of ISCs manifests itself only after the early 1990s. Before that, all supply and service companies present a more or less similar pattern. The formation of ISCs seems to have transferred the locus of innovation of the upstream sector from IOCs to ISCs, and ISCs become the leading technological innovators of the sector. In fact, ISCs were responsible for the largest share of resurgence of innovative activities after the mid-1990s, generating about 40% of total innovations and about 70% of the share of top 50 patentees. Compared to their marginal share in the early 70s, this considerable rise in the share of ISCs' innovative activities needs particular attention. We discuss this issue in section 6.5.3, after exploration of the innovation strategy of different players in the next section.

6.5.2. Dynamics of innovation strategy: size and direction

In this part, we examine the innovation strategy of different types of actors over time to examine the third hypothesis of this PhD. The *direction* of innovation strategy is the main concern. We ask whether different types of players follow technological diversification or specialization in different periods. We also trace firms' average size of innovative activities to control for the effect of *size* on *direction*. This is because the larger the *size* of innovative activities, the wider the possibility of technological diversification. We need to understand which actors, in which periods, are diversifying or specialising. Also, to what extend can their behaviours, in conjunction with each other, be associated with the nature of knowledge base complexity in different periods. Since early p2 seems to be the turning point, I explore the broad trends before and after early p2. They correspond to two major phases of the industry, over which knowledge base complexity and Schumpeterian patterns of innovation expressed different patterns.

Following previous research (e.g. Cantwell and Santangelo, 2000; Cantwell and Vertova, 2004), the reciprocal of Coefficient of Variance (CV) of Revealed Technological Advantage (RTA) is used in order to measure the diversity (Div) of the knowledge base of each firm:

$$Div = \frac{1}{CV_{RTA}} = \frac{\mu_{RTA}}{\sigma_{RTA}} \tag{1}$$

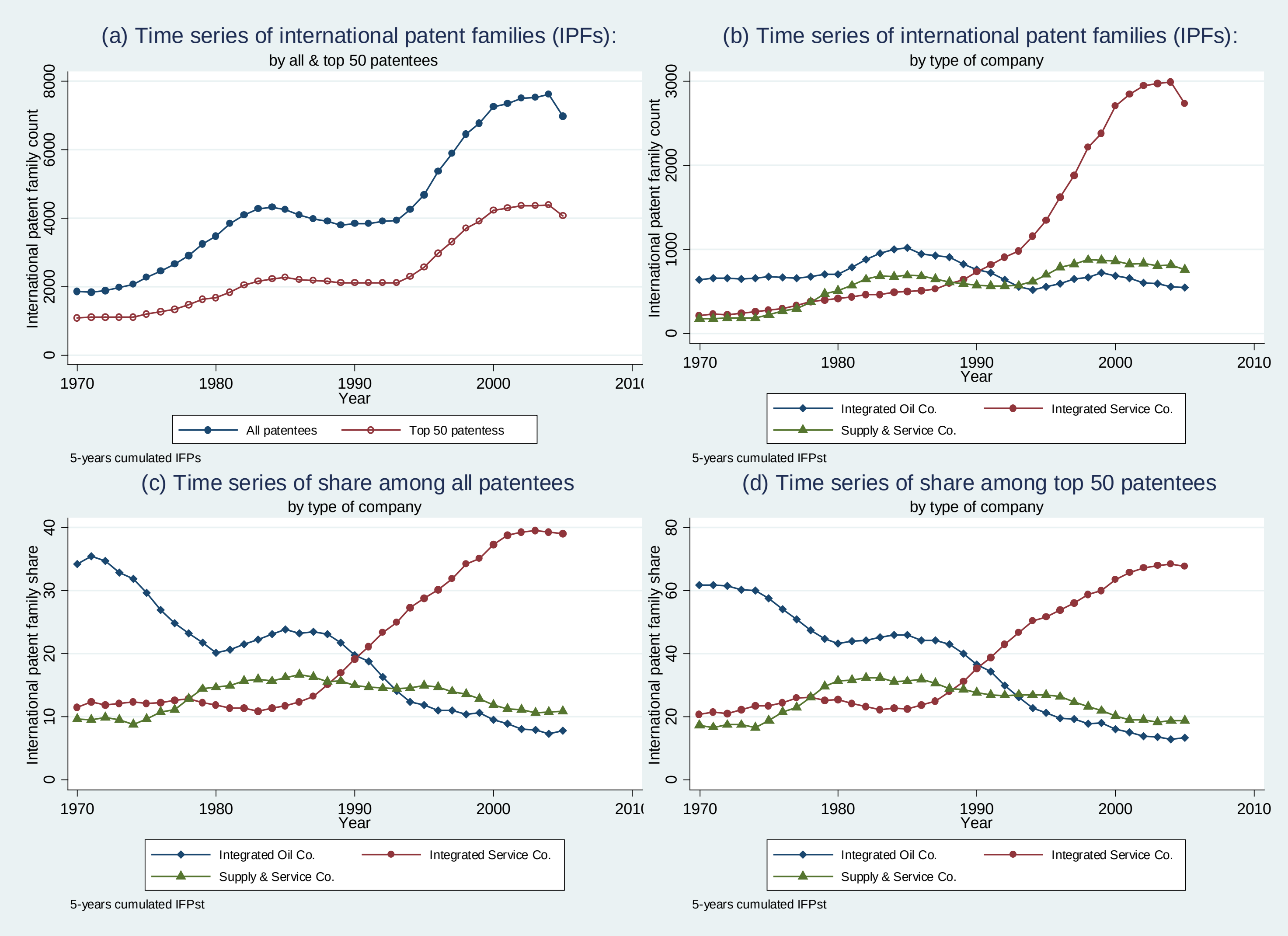
Where: $$\mu_{RTA\,j} = \sum_i RTA_{ij} / I \tag{2}$$

$$\sigma_{RTA\,j} = \left[\sum_i (RTA_{ij} - \mu_{RTA\,j})^2 / (I-1) \right]^{1/2} \tag{3}$$

$$RTA_{ij} = (n_{ij} / \sum_j n_{ij}) / (\sum_i n_{ij} / \sum_{ij} n_{ij}) \tag{4}$$

When ***n*** is the number of patents in class ***i*** (1 …, I) for firm ***j*** (1 .., J).

Figure 6-5 The trend of patenting by different types of companies



RTA is a proxy for technological specialization first suggested by Soete (1980). It is calculated for each technological class ***i*** in company ***j*** according to the above equation (4). This index measures a relative specialization of each company according to the share of a particular class in a firms patent portfolio weighted by share of that class over the whole industry. As explained by Cantwell and Santangelo (2000), the inverse of CV of RTA is a direct measure of diversification. It is high when a firm is relatively active in many technological fields and is low when a firm is specialized in a few fields and does not operate in many other fields.

Only firms with a patent stock of at least 10 in each sub period are included in the analysis to avoid the problem of small numbers. Small numbers could create randomly very high or low RTAs. As a result, Div value may become meaningless (Cantwell and Vertova, 2004). I calculated Div mean value as the average diversity (ADiv) of the knowledge base of different types of companies in different periods (figure 6.6). The measures are based on 7-digit IPC class, as before. In order to control for the effect of innovation size on ADiv, the Average innovation Stock (ASto) of different companies in different periods is also presented in figure 6.7. It is presented on a logarithmic basis, because the size distribution is highly skewed. We can better understand whether firms are diversifying/specializing, as a result of size change (positive or negative growth) or following a genuine strategy with regard to change in their knowledge environment. In other words, we can explore the dynamics of actors' innovation strategy in terms of both *direction* (diversification vs. specialization) and *size* (positive or negative growth) at the same time.

The figures 6.6 and 6.7 illustrate that on average all three types of companies are becoming relatively more specialized (less diversified as reflected in the decline of ADiv) before early p2, in spite of their size expansion. In other words, although all three types of companies are expanding their innovative activities, they are focusing more on their own area of specialization; therefore the development of knowledge base of the industry before early p2 is achieved by a *specialized growth* strategy in all three types of companies. This strategy is consistent with the rise of both breadth and depth complexity before p2, as predicted by the third hypotheses (H3). Table 6.4 summarizes the innovation strategy of three types of companies before and after early p2.

These specialized companies govern the depth complexity of the sector within that particular domain of specialization where they have core competences. This is consistent with *narrow cumulativeness* which motivates companies to build their own area of specialization and accumulate knowledge within it. The breadth complexity of the sector is also governed largely through a more market-based decentralized coordination mechanism aligning different specializing companies. This evidence suggests that none of the actors see technological diversification as an efficient strategy to respond to the specific knowledge requirements of the industry. In contrast they differentiate themselves by sticking to and deepening their own area of technological expertise. The breadth of knowledge at sectoral level is expanded by technologically specialized companies operating beside each other covering the increasing range of knowledge domains. New technological fields are added to the sectoral knowledge base mostly by specialized companies. This is possible, because systemic complexity is decreasing and technical interdependencies are not pervasive. Markets are perceived as effective to mix and match the breadth of the jigsaw puzzle of sectoral knowledge base.

Since early p2, the technological pathway of different types of companies has begun to diverge and a new knowledge governance system is emerging. ISCs keep growing at a high pace (given the logarithmic scale of the figure). SSCs also continue their upward trend, while IOCs reduce their average innovative activity. It seems that ISCs benefited the most from acceleration of the outsourcing trend in p2 and have managed to master the technological requirements of the expanding services market. This is reflected in their continued hyper growth, as the trend of ASto after early p2 suggest. More importantly, they began their unique strategy of technological diversification as reflected in the rise of ADiv. Therefore the ISCs' behaviour after early p2 is characterized as *diversified growth* strategy. This result is consistent with the prediction of the third hypothesis (H3) of this research. We argue, with evidence, that when the systemic knowledge complexity of the sector increases, we expect at least some systems integrator actors to become technologically diversified. In contrast, both IOCs and SSCs followed a *specialization strategy* over p3. We can compare and contrast the innovation strategy of different agents before and after early p2 in table 6.4.

Exploiting the combination of economy of scope alongside economy of scale justifies this concurrent expansion of size and diversity in ISCs. Compared to other agents, they managed to benefit from the synergies and interrelatedness between the diverse and increasing number of technological domains in their knowledge portfolio. In fact the technological behaviour of ISCs looks like a *new entity* in the sectoral innovations system which deals with technological interrelatedness and systemic interactions within different domains of the knowledge base. We do not see such strategy in other agents before or after p2. This is a very aggressive growth strategy towards technological diversification. By 2005, about 70% of all innovation activities of the top 50 patentees were concentrated within just four major integrated and technologically diversified service companies[25].

In contrast to ISCs, IOCs after p2 reduced the size of their innovative activities (decline of ASto) and followed a technological specialization strategy (significant fall of ADiv). This seems to be a continuation of the specialisation strategy that they employed before early p2. They aim to refocus on technological ‘core competencies’ and leave non-core technological activities for other companies. We could characterize their behaviour as *specialized de-growth* or *refocusing* strategy. SSCs also continued their previous strategy, operating a *specialized growth* strategy after p2.

The combination of these three different innovation strategies after p2 clearly suggests a radical shift in the vertical division of knowledge, transformation of organizational patterns of innovation and emergence of a new knowledge governance system. The ISCs go for strong *diversified growth*, the IOCs follow *specialized de-growth* and SSCs continued their previous *specialized growth* strategy. We interpret this new configuration as a “social solution of technical problems in complex systems” (Johnson, 2005), which defined new roles for the old players.

On the one hand, higher systemic complexity and interactions between different technological domains defined a new role served by ISCs. They increased their role in coordination and integration of new technological domains. On the other hand, ISCs

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[25] Schulmberger, Halliburton, Baker Hughes, Weatherford

explore combination and recombination possibilities and create new relationships between different technological domains to find a productive opportunity.

Figure 6-6 Dynamics of innovation strategy (direction) by the type of company

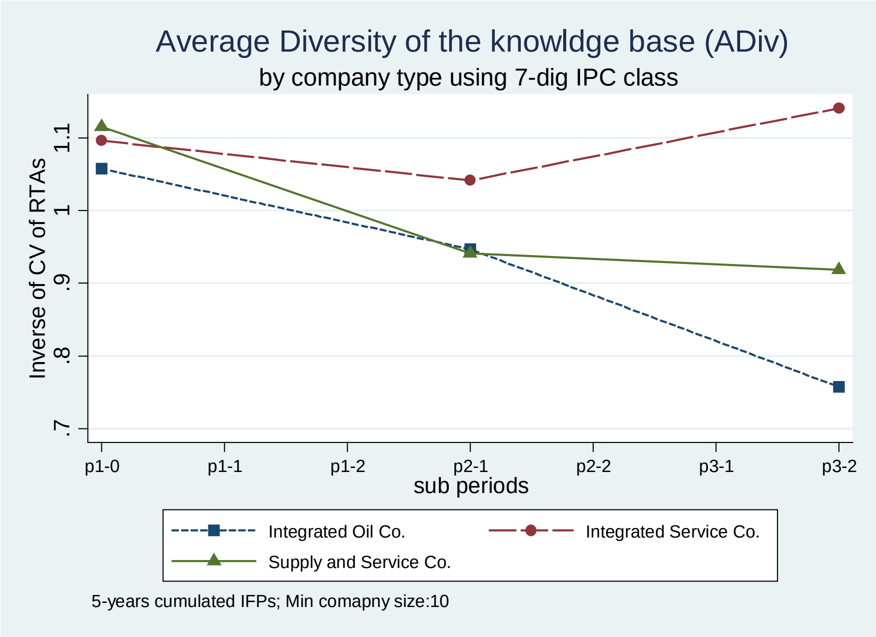
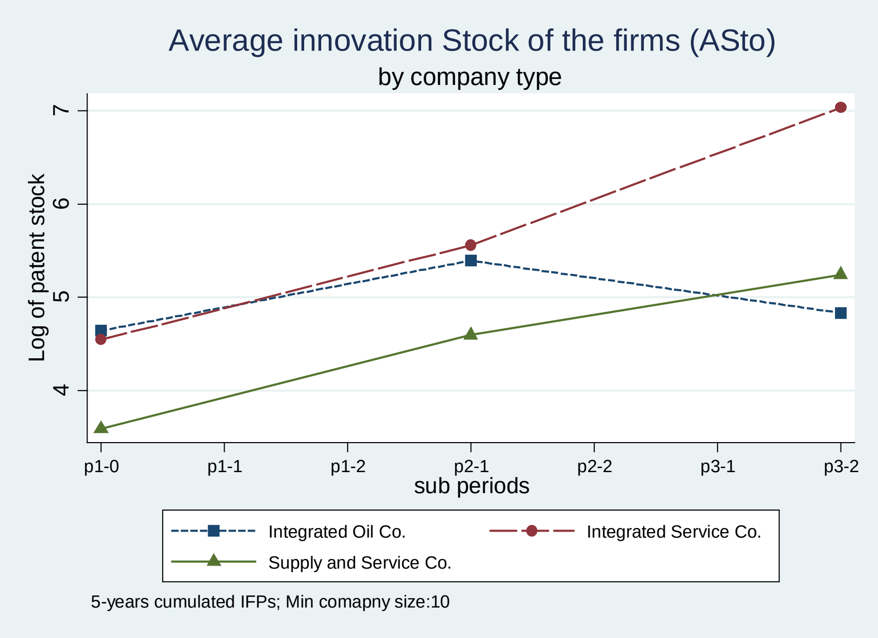


Figure 6-7 Dynamics of innovation strategy (Size) by the type of company



Therefore, operation of these technologically diverse companies creates extra systemic knowledge base complexity. The ISCs' move towards *total solutions* and *integrated* *services* which began in late 1980s could be viewed as both a consequence and a driver of higher systemic complexity in the knowledge base of the upstream industry.

What triggered this new knowledge governance system was outsourcing and the refocusing of IOCs. Outsourcing should not be seen simply as transfer of some functions from one entity to another. Increasingly, the complexity of upstream projects required a *new* function to be served in the sector. This created a *new* demand by IOCs for *total solutions,* seeking structurally a new kind of service. The old structure of the system of innovation was not able to meet this new function, because agents to manage the added complexity did not exist. A new capability was required to mix and match increasingly diverse and specialized pieces of knowledge and handle the technological expertise of complex big projects. ISCs embraced this systemic complexity and emerged as the new technology leaders of the sector. In parallel SSCs also improved their capability to manage the excessive additional depth complexity of many knowledge domains.

Table 6-4 Dynamics of innovation strategy of different types of companies

Type of companies	**Before early p2**	**After early p2**
Integrated Service Companies	Specialized growth	Diversified growth
International Oil Companies	Specialized growth	Specialized de-growth
Specialized Service and Supply Companies	Specialized growth	Specialized growth

6.5.3. From ‘vanishing' to 'emerging' hand: toward a dynamic theory of knowledge governance

The results provided in the previous section supports the third hypothesis of this research, establishing a dynamic association between knowledge base complexity and governance of sectoral knowledge bases. In addition, some novel aspects of empirical evidence explored in this chapter offer new insights for the refinement and extension of existing theoretical frameworks about dynamics of governance structures (Jacobides and Billinger, 2006; Nootboome, 2004, Rosiello, 2007). I argue that a co-evolutionary framework proposed by Jacobides and Winter (2005) provides a more articulated and comprehensive theoretical account, if it is combined with the dynamic and three-dimensional perspective to knowledge base complexity. In this extended framework, dynamics of knowledge governance is explained according to co-evolution between transaction costs and firm capabilities.

Previous research provides valuable insights about the drivers of both technological specialization (dis-integration) and technological diversification (re-integration) in certain conditions. For example, recent waves of specialization are explained by the theory of 'vanishing hand' (Langlois, 2003), extension of 'modularity' into knowledge domain (Baldwinn and Clarck, 2000; Ernst, 2005a) and emergence of markets for technology (Snaches and Mahoney, 1996; Arora et al., 1997). Also Brusoni (2003a) explains the strong forces behind specialization and dis-integration. Technological diversification is also explained by the theory of 'multi-technology corporations' (Granstrand et al., 1997), 'cognitive limits of specialization' (Brusoni, 2005), and the role of 'systems integrators' in complex sectors (Brusoni et al., 2001; Brusoni, and Prencipe, 2001a and 2001b; Pavitt, 2003, 2005).

However, there are at least two novel aspects in the upstream petroleum industry which have not been well articulated in previous studies. First, the upstream sector presents a *full dynamic cycle* from integration to disintegration and back to what I call *neo-integration*. I will explain why the term *neo-integration* is preferred, instead of *re-integration*. Yet, the literature cited in the previous paragraph is dominated by *static* approaches. They tend to explain the formation of particular governance structures under particular conditions, but are less concerned about the drivers of change or *dynamics of governance structure*. In other words, they do not explain how firms' knowledge boundaries may change over time. Even if they take a dynamic approach, they often analyze a *partial cycle*, either a move towards diversification or specialization (e.g. Acha and Brusoni 2008; Busoni and Prencipe, 2006). There are very rare examples where both cycles are analyzed together in a unified theoretical framework. An exception is Cacciatori and Jacobides' (2005) analysis of the full cycle in building industry first towards dis-integration and then back to re-integration.

Second, and with regard to neo-integration, the literature often discusses the drivers of *backward vertical* integration in knowledge domains. In other words, it explains why systems integrators extend their knowledge boundaries into the domain of their suppliers when production is outsourced (Brusoni, and Prencipe, 2001a and 2001b). What is less discussed is the situation where some suppliers (Integrated service companies in the case of upstream petroleum industry) gradually take a *forward vertical integration* step and present *an aggressive diversified growth* innovation strategy. This is what I call *knowledge neo-integration* to distinguish it from *re-integration. Re-integration* implies bringing back what has been outsourced before. *Neo-integration* implies taking a new responsibility which serves a new function in the sector.

It could be misleading to view this transformation as re-distribution of existing knowledge activities. It is better understood as 'emergence' of a new ‘role’ (Brusoni, et al., 2009) occupied by ISCs to facilitate the governance of 'emergent' systemic knowledge base complexity. In other words, it is interpreted as a system-wide response to qualitatively new demand (explained in chapter 4) and technologically excessive systemic complexity (explained in chapter 5). By this, I do not deny that ISCs also take some responsibilities of IOCs, but what emerged in the sector is clearly far more than that. This growing trend towards one-stop-shop integrated solutions in the domain of service provision is often explained by seeking higher profit margins and revenues in volatile markets (Davies, 2005). However, we still need to explain why ISCs became so aggressive in knowledge generation and technology diversification, in addition to their new approach in service provision.

I think Jacobides and Winter’s (2005) co-evolutionary framework is a very promising starting point to move towards a dynamic theory of knowledge governance. It is originally developed to explain the dynamics of vertical scope of production or industry architecture. The great advantage of this framework is its unified approach to explanation of both cycles of disintegration and re-integration processes in terms of co-evolution between transaction costs and firm capabilities. Transaction-cost is perceived as a partially endogenous variable determined by firms' choices.

According to this framework, natural selection forces tend to push firms to higher specialization in those segments where they have superior capabilities and therefore higher profit margins. Their capability differences provide further incentives to intentionally reduce transactions costs, as they perceive higher gains from trade with each other. Higher specialization and change in vertical scope shapes a trajectory through which capability development processes are affected. This processes leads to a new distribution of capabilities along the vertical chain which may result in a new mix of participants and industry structure. I think this framework has great capacity to explain the dynamics of vertical scope of knowledge as well, if the dynamic and three-dimensional perspective to knowledge base complexity is considered.

The first period of the upstream petroleum industry illustrates that dominance of breadth complexity is associated with prevalence of technological specialization. By definition, breadth complexity implies low transaction costs across different knowledge domains. Limited interdependencies allow firms to gain from technological specialization which shapes further their trajectory of capability accumulation. The transaction costs have been further reduced endogenously, as IOCs' outsourcing schemes show (chapter 4). This trend suggests that breadth complexity could be efficiently managed by more market-based decentralized modes of knowledge governance. The industry ended with a new mix of more specialised actors, each focusing on a relatively narrower scope after the dis-integration cycle before early p2. If a snapshot of this period is taken, the 'vanishing hand' idea (Langlois, 2003) seems applicable. However, the validity of this idea stops when industry goes back to neo-integration after early p2.

Jacobides and Winter's (2005 p. 406) framework predicts that the same variables may operate in a reverse direction toward integration. This may happen "when this cycle of specialization exhausts the benefits it can offer, or whenever a *new knowledge base* comes about that relies on a more integrated structure". As a result "integrated firms may *displace* the specialized ones, and inverse process takes place." (emphasis added). The case of upstream petroleum industry also presents an attractive example of this cycle, when a "new knowledge base" with systemic complexity emerges and pushes ISCs toward integration and diversification.

Jacobides and Winter's (2005) framework again seems applicable to the *neo-integration* cycle if dynamic and three-dimensional perspective to the knowledge base complexity is considered. The *neo-integration* process is often triggered with a widening gap between what a vertically specialized structure could supply and what a changing environment demands (Cacciatori and Jacobides, 2005). This fits very well with the changing nature of the oil industry. The efficient exploitation of increasingly complex upstream projects was not possible with a highly specialized system. System-wide efficiencies required the combination of a different and increasing range of knowledge domains. The dominance of systemic complexity, by definition, means high and increasing transaction costs which encouraged higher integration in ISCs.

IOCs motivation to simplify the organization of complex projects also reinforced this process where they released some integrative and project management tasks to some powerful service companies. Although they kept their system integration role at the top end of the value chain, the generation and integration of new technological knowledge mostly became the occupation of ISCs. These pull and push forces created a new intermediate market for integrated and total solutions. A new business of all-in-one services emerged, while the transaction-cost of discrete services increased. This is because the risk of possible mis-match between different products or services with the other parts of the system is high.

This self-reinforcing mechanism is amplified through two main loops which gradually led to high knowledge generation and greater technological capability in ISCs. First, the new market for integrated solutions offers higher profit margins and a more stable revenue stream (Davies, 2005). This enables ISCs to conduct more R&D and innovation investment creating a financial loop. The second loop is of a cognitive type stemming from increasing systemic knowledge base complexity. Compared to other SSCs, ISCs have deeper access to systemic and architectural knowledge. Therefore, wider knowledge generation and innovation space is open to them. This knowledge enables them to be more aware of new innovation opportunities, particularly of a systemic type. It can also offer them higher cognitive ability to innovate through recombinative processes. The operation of these financial and cognitive loops can explain the surge of technological capabilities in ISCs. This is consistent with the view of some scholars who argue that vertical integration can lead to superior innovation ability (Raynor and Christensen, 2002; Christensen et al., 2002).

A new distribution of technological capabilities emerged in which new agents play new roles. This process engendered the emergence of a new *system integrator* in the same sector. IOCs have been the traditional systems integrators at the top end of the value chain. ISCs became new systems integrators after the middle of the 1990s, but with a different purpose at a different point of the value chain. IOCs' are more concerned with architectural or systemic knowledge of the whole upstream process. This involves integration of technological knowledge with geological, financial, economic and even social and political knowledge. This capability enables them to design and implement efficient portfolio of projects in a variety of geopolitical locations and over different time spans. ISCs are systems integrators more at the level of oil production facilities which increasingly involves combination and integration of advanced technologies. Of course, co-existence of multiple systems integrators which operate at different levels of the value chain is not a new phenomenon, as it is observed in other very complex sectors such as the aircraft industry (Hobday, 1998).

This tentative extension of the co-evolutionary framework (Jacobides and Winter, 2005) into knowledge domains can shed light on novel aspects explored in the dynamics of the upstream petroleum sector. This conceptual framework provides valuable insights to explain the *full cycle* of dynamics of knowledge governance. In addition, the suggested framework explains why in particular industries some actors may take an *aggressive diversified growth* innovation strategy and follow a *forward integration* approach in knowledge domain. As explained, previous research either takes a static view to knowledge governance or at best addresses a *partial cycle* of industrial dynamics. Also when vertical integration as a *partial cycle* is considered, most previous research has focused on backward integration in the knowledge domain by systems integrators. The suggested framework aims to explain both dis-integration and neo-integration phases in terms of the same set of variables operating in reverse directions. Accordingly, the dynamics of knowledge governance can be explained in a unified framework integrating the insights of previous research. It is possible to understand why a sector first experiences a 'vanishing hand' pattern. It also clarifies why this trend may stop and turns back into a neo-integration pattern when the 'emerging hand' of new systems integrators such as ISCs becomes visible.

6.6. Conclusion

This chapter was an intellectual attempt to explain how the changing nature of knowledge base complexity is associated with the governance structure of sectoral knowledge bases. It explained that the question of knowledge governance has been the subject of at least two relatively separate research programs which look at different, yet complementary aspects. First is the Schumpeterian tradition which tends to focus on the relative role of small vs. big and new vs. incumbent firms with regard to their contribution in the innovation processes. The second tradition is the combination different branches of organizational studies which commonly use a *functional* approach to the analysis of knowledge governance. This tradition tends to look at the *division of knowledge* between different players and their particular functions in the governance of sectoral knowledge base. In other words, the role of different actors is analyzed collectively and systematically to examine the dynamics of their innovation strategy in terms of *direction* (specialization vs. integration) of technological activity. It is clear that the two research programs highlight different aspects of knowledge governance and are complementary.

Two hypotheses are developed based on these two analytical frames addressing the association between dynamics of knowledge base complexity and governance of sectoral knowledge. The former, based on Schumpeterian tradition, suggests that dominance of breadth complexity is more associated with Schumpeter Mark I, while the rise of systemic complexity implies a shift towards Schumpeter mark II. The latter hypothesis, based on the functional approach, suggests the dominance of a technological specialization strategy for innovators under breadth complexity. It also predicts the shift of systems integrators towards technological diversification when systemic complexity increases.

This chapter offers three contributions in order to examine the suggested hypotheses. First, a methodology has been suggested in order to capture the dynamics and evolution of mode of knowledge governance under both different frames. The second contribution is the application of a suggested methodology in the upstream petroleum industry which illustrated novel empirical observations in the dynamics of the governance system of sectoral knowledge base. These empirical findings also brought new insights regarding the dynamic theory of governance of sectoral knowledge base, as the third novel aspect of this chapter.

The second hypothesis of this PhD is supported by empirical observation. A shift of Schumpeterian patterns of innovation from Mark I to Mark II after early in period 2 is shown, when systemic knowledge base complexity increases. In addition, it is shown that the dynamics of *technological opportunities* is not sufficient to explain this shift of *mode*, although it can explain changes in the *degree* or strength of existing Schumpeterian patterns. However, if the dynamics of *technological opportunities* are analyzed in combination with *knowledge base complexity* as two different dimensions of technological regimes, they convincingly explain the dynamics of Schumpeterian patterns both in terms of *degree* and *mode*. In other words, a shift in the dominant type of complexity could alter the Schumpeterian mode, while a change in opportunities tends to weaken or strengthen the existing mode without altering it.

The analysis of the upstream petroleum industry showed that small and new innovators could exploit increasing technological opportunities most when knowledge base complexity is predominantly of the breadth type and systemic complexity is decreasing. This resembles most, the features of Schumpeter Mark I mode. In contrast, when systemic complexity becomes dominant in the sector, the rise of technological opportunities is relatively more beneficial to large and incumbent companies. This situation characterizes the Schumpeter Mark II mode. As a result, the transformation of Schumpeterian pattern of innovation from mode I to mode II can be understood with reference to increasing systemic complexity of the knowledge base. In other words, the nature of knowledge components underlying the sector may have not change considerably. However, the intensity of interactions between knowledge components has increased, leading to higher systemic complexity and knowledge cumulativeness of the sector in recent periods. This situation has reinforced the relative position of incumbents compared to new firms and increases the barriers to entry. Put it differently, technical change has been more of ‘competence-enhancing’ type (Tushman and Anderson, 1986) where incumbents have higher absorptive capacity (Cohen and Levinthal, 1989) to assimilate new but similar knowledge.

This analysis shows that high technological opportunities can reduce the gap between small and big innovators when systemic complexity is decreasing (Schumpeter Mark I). However, high technological opportunities are most likely to widen the gap between small and big innovators, if systemic complexity dominates the sector (Schumpeter Mark II).

The third hypothesis of the PhD is also supported by empirical evidence. It is shown that before p2 when breadth complexity is increasing and systemic complexity is decreasing; all three types of actors take a *specialized growth innovation strategy*. However after early p2 when systemic complexity increases sharply, Integrated Service Companies emerge as the new systems integrators of the sector with *aggressive diversified growth innovation strategy* to cope with this excessive systemic knowledge base complexity.

In addition, it is shown that there is no *unified theory* which could consistently explain two novel aspects of the dynamics of the knowledge governance explored in the upstream petroleum industry. The first novel aspect is the *full cycle* of *dis-integration* and back to what was characterized as *neo-integration*. The second is the emergence of integrated service companies as the new system integrators following a *forward integration* strategy. We observed that they became leading innovators following *aggressive diversified growth innovation strategy*. Some valuable but partial insights can be drawn from various strands of research to explain these two novel aspects, yet not in a unified theoretical framework. Nonetheless, a co-evolutionary framework (Jacobides and Winter's, 2005) originally developed to explain the dynamics of vertical scope of production is proposed to be extended to the knowledge domain, as it seems very promising for the purpose of theoretical unity. This framework combines transaction costs as a partially endogenous variable and firm capabilities in order to explain the dynamics of governance structures. If the three-dimensional perspective to knowledge base complexity is integrated in the original framework, a dynamic theory of knowledge governance can be drawn. A tentative application of this unified theoretical framework in the case of upstream petroleum industry seems very promising.

The dominance of the *specialized growth innovation strategy* by most of agents in the *dis-integration* period is explained by the relative low transaction costs stemming from dominance of breadth complexity. The emergence of Integrated Service Companies as leading actors with aggressive *diversified growth innovation strategies* in the *neo-integration* period is interpreted as a sector-wide response to the emergent systemic complexity. It is explained that systemic complexity involves high transaction costs in knowledge generation processes and requires new system integration capabilities. In fact integrated service companies are understood as the new agents in the sectoral innovation systems of upstream petroleum industry which gradually emerge to serve a new function. This new function is the governance of excessive systemic complexity emergent in the most recent period. While the analysis of the *dis-integration* period provides support for the *vanishing hand* idea (i.e. reliance on external knowledge sources increases), the *neo-integration* period can be seen as the *emerging hand* of corporate knowledge management becoming visible when a sector experiences increasing systemic complexity.

The findings of this chapter extend our understanding of the drivers of change in systems of knowledge governance within two complementary traditions. Accordingly, a dynamic theory of governance of knowledge base complexity is suggested in *Schumpeterian* and *functional* versions. This facilitates integration of both traditions. It is possible, on this basis, to analyse the role of geography in coping with the dynamics of complexity and how knowledge is integrated and coordinated across geographical distances, the subject of the next chapter. This paves the way to understand the role of knowledge base complexity in technological catch-up of latecomer countries, and how geographical pattern of innovation can be affected by the dynamics of knowledge base complexity.

7. Chapter 7: Geography of knowledge base complexity

7.1. Introduction

In the previous chapter, I investigated the dynamics of sectoral and organizational patterns of innovation as two aspects of governance of knowledge base complexity in the upstream petroleum industry. This chapter extends the analysis to explore the possible implications of the evolution of knowledge base complexity for international geographical patterns of innovation and catch-up processes. Although the SIS literature has proposed hypothetical relationships between different dimensions of technological regimes and geography of innovation since the early developments of the research agenda (Malerba and Orsenigo, 1997; Breschi, and Malerba, 2000), this relationship has rarely been empirically studied (Breschi, 2000 is an exception at sub-national level). Explicit analysis of the *dynamics* of this relationship is even scarcer within SIS literature, although some studies in the geography of innovation has marginally touched upon this issue. I found only two studies which directly address the role of technological complexity in the geography of innovation (Vertova, 2002) and catch-up processes (Ernst, 2005b).

The present research is interested in investigating the extent to which the sectoral innovation system is open to late comer countries and allows for catch-up. I ask here whether there is a possibility of catch-up within the upstream petroleum industry. 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 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. It is clear that 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 these national territories. Nonetheless, I am asking the question at national level in order to understand what factors may impede or stimulate the emergence of new innovative agents or relocation of existing innovators within new territories?

Contributing factors to change and dynamics of geography of innovation are potentially very diverse and operate at different levels. These include broad global trends such as globalization, firm 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 such as technological regimes, and cognitive dimensions of the industry such as complexity are another set of important factors (Lee and Lim, 2001; Vertova, 2002, Ernst, 2005b, Sorenson et al., 2006). This chapter focuses on this last element which has been a neglected area.

This chapter offers three contributions at theoretical, methodological and empirical levels. First, it seeks to resolve some of the puzzling conceptual implication of complexity for geography of innovation raised in the literature arguing both for concentration attached to higher level of complexity (Vertova, 2002; Sorenson, 2005) and against it (Ernst, 2005b,). I argue that this puzzle is largely due to the lack of distinction between different dimensions of complexity which could have different and opposite geographical implications. Taking a dynamic and three-dimensional perspective to complexity, I also explain how change in the dominant type of complexity can have different geographical implications. Second, a methodology is proposed which allows tracking of the dynamics of geography and catch-up processes, and examination of their association with the dynamics of knowledge base complexity. The third contribution is the application of the suggested methodology in the context of the upstream petroleum industry. This is an empirical extension of previous research on geography of innovation (Lee and Lim, 2001; Vertova, 2002, Ernst, 2005b, Sorenson et al., 2006). In addition, the findings shed light on the limits of internationalization theory of innovation, and pave the way for a dynamic theory of geography of knowledge base complexity.

This chapter is organized in 8 sections. Section 7.2 employs the literature on the geography of complexity to propose some clarifications and formulate a hypothesis. Section 7.3 provides an overview of the hierarchy of innovator countries and their relative contributions. The geographical data are explained in section 7.4. Exploration of the dynamics of international geography of innovation in upstream petroleum industry and examination of the catch-up hypothesis are the subjects of sections 7.5 and 7.6. Section 7.7 discusses the relevance of the empirical findings of the two previous sections with available theories. It suggests that the dynamic and multi-dimensional perspective to knowledge base complexity can offer analytical value and pave the way for a dynamic theory of the geography of knowledge base complexity.

7.2. 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. They empirically supported this idea showing the patenting behaviour of big innovator companies. 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).

From these definitions, it is clear that Pavitt’s emphasis is on *systemic* complexity where interactions are dense and unpredictable and therefore the knowledge is hardly modular and decomposable. Similarly, Breschi (2000) argued that the more the knowledge base is tacit, complex and part of a larger system, the more is there geographical concentration of the innovations, 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 constrains on knowledge flows. His empirical evidence suggests that 10-15% of the variety 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 the sector.

However, Ernst (2005b) documented a paradoxical case. In spite of increasing extraordinary cognitive and organizational complexity, the cheap design industry actually experienced geographical *decentralization*. Ernst (2005b) tackles the important question: ‘What makes 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 could involve at least three types of gains. First, it reinforces specialization and facilitates knowledge growth at the level of components and modules. Second, it lowers costs, if the relocation goes to cheap countries. Third, it facilitates local customization according to the peculiarities of demand in each location.

Given the possibility of modularity, it seems that Ernst's (2005b) argument applies when breadth complexity dominates and systemic complexity decreases. Nonetheless, he does not distinguish between different types of complexity. Since the knowledge base of the industry is relatively decomposable to 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. Under these conditions, where systemic complexity is low or lowered by transformation to breadth complexity through modularity strategy, 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.

However in the case of high systemic complexity the situation is very different. Access to systemic or architectural knowledge is required when interdependencies are high, because one piece could have radical and unpredictable impacts on the outcome. As a result, it is very difficult for distant players to innovate when systemic complexity is high. In addition, diffusion of knowledge with systemic complexity over long distances is very challenging, because some pieces might be missed or distorted along the way. It also implies higher absorptive capacitates in recipients (Sorenson et al., 2006; Sorenson, 2005). 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. This theoretical analysis provides a basis to answer the third question of this research:

Q3: What are the implications of dynamics of technological complexity for the international geography of innovation and catch-up processes?

According to that theoretical account, the fourth and final hypothesis (H4) of this research proposes the following answer:

Hypothesis 4: 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.

7.3. Hierarchy of innovator countries in upstream petroleum industry

Before the analysis of the dynamics of the international geographical patterns of innovation, it is good to get some insights about the relative position of different countries. Table 7.1 provides the ranking of innovative countries using location of patent inventor data. As explained in chapter 3, for international comparisons inventors' country (IC) is the most relevant data for geographical studies.

We observe in table 7.1 a very high concentration of innovative activities in a few top countries. More than 54 percent of all inventions between 1970 and 2005 have been located in the United States. The UK, France, Canada and Germany are next but far behind the US. These top 5 innovators are responsible for more than 80 percent of total patents and the top 10 for more than 90 per cent. It is interesting that some resource-rich countries, which are not usually considered as innovators such as Saudi Arabia and United Arab Emirates, appear in the list although they are near the bottom with marginal shares.

Another noticeable point is the emergence of three strange countries of British Virgin Islands, Panama and Netherlands Antilles in the list of innovative countries. These are countries where some big companies have registered offices probably due to tax and other regulatory issues. Since for some of the patents with missed location country of inventor the assignee countries are used (explained in chapter 3), these countries have come up in the list. For subsequent analysis I remove these countries as they are not relevant to the *real* geography of innovation.

Table 7-1 Ranking of countries based on location site of inventors

Rank	Country	Code	IPF	%IPF	%CUM
1	United States of America	US	21300	54.47	54.47
2	United Kingdom	GB	3946	10.09	64.56
3	France	FR	2902	7.42	71.98
4	Canada	CA	2013	5.15	77.12
5	Germany	DE	1679	4.29	81.42
6	Norway	NO	1569	4.01	85.43
7	Netherlands	NL	1225	3.13	88.56
8	Japan	JP	684	1.75	90.31
9	Russian Federation	RU	390	1	91.31
10	Sweden	SE	346	0.88	92.19
11	Australia	AU	287	0.73	92.93
12	Italy	IT	277	0.71	93.64
13	Brazil	BR	182	0.47	94.10
14	Belgium	BE	181	0.46	94.56
15	Virgin Islands (British)	VG	170	0.43	95.00
16	Switzerland	CH	165	0.42	95.42
17	China	CN	158	0.4	95.82
18	Panama	PA	133	0.34	96.16
19	Denmark	DK	107	0.27	96.44
20	South Africa	ZA	93	0.24	96.68
21	Austria	AT	91	0.23	96.91
22	Venezuela	VE	84	0.21	97.12
23	Finland	FI	81	0.21	97.33
24	United Arab Emirates	AE	80	0.2	97.53
25	Singapore	SG	79	0.2	97.74
26	Saudi Arabia	SA	68	0.17	97.91
27	Malaysia	MY	52	0.13	98.04
28	Hungary	HU	51	0.13	98.17
29	India	IN	49	0.13	98.30
30	Israel	IL	46	0.12	98.42
31	Ukraine	UA	41	0.1	98.52
	Other	Other	578	1.48	100.00
	Total	Total	39107	100	100.00

IPF: International patent family

CUM: Cumulative percentage

7.4. Geography data

Although inventor country (IC) is usually used in geographical studies of innovation, it might be misleading if we are to explore catch-up countries and analyze catch-up processes. This is because these data do not distinguish between innovations performed by domestic or by foreign companies in a country. If we are to understand the possibility of catch-up, the changing balance of ownership vs. location could have different implications. This is because in extreme cases, we might have situations where big multinational companies just relocate their R&D centres to follow market expansion strategies, with limited knowledge spillovers to local companies and limited local innovation capacities. Theoretically, it is possible to imagine some countries becoming attractive locations for foreign and international companies to carry out innovative activities where the share of local innovators stays marginal. Tax, cost, or other market related factors may be incentives for such relocations.

In order to tackle this issue in the data, we need to know who owns and may control the innovations and where are their original countries. Unfortunately, our dataset does not specify the original country of each company. Although the assignee country of each patent family exists in the data set, this information does not solve the problem. 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. In order to find the original country of the companies, I 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 innovative activities.

Using this concept, I am able to capture the relative position of countries in producing upstream knowledge and technology. I am also able to track the extent of inventive activities located in each country distinguishing between those done by local vs. non-local companies or by collaboration between them. This distinction, as will be seen, provides some insights about the role of international knowledge flows in building local technological capabilities and catch-up processes.

7.5. Geographical patterns of innovation

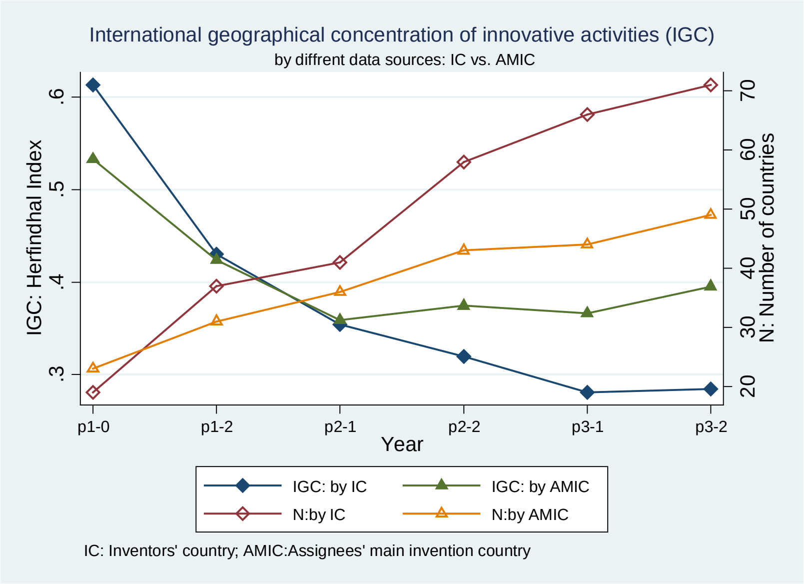
In this section, I analyze the evolution of geographical concentration of innovation in different countries, the number of countries and the role of (companies from) new countries over time. These are considered as measures of international geographical patterns of innovation. These measures are the extension of the similar proxies used in the analysis of sectoral innovation systems in the previous chapter, extended to the geographical domains. According to these measures, we can examine the fourth hypothesis of this research with regard to availability and speed of catch-up processes in different periods and answer the third question raised in section 7.2.

7.5.1. International geographical concentration of innovative activities

The dynamics of international geographical concentration (IGC) of innovation across different countries are presented in figure 7.1 using 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.

Figure 7-1 International geographical concentration of innovative activities (IGC)



The meaning of these trends is that innovative activities, if considered by their owner countries (AMIC), became even more concentrated in p3-2 than its level two decades earlier in p2-1. In other words, the majority of technologies of the upstream petroleum industry is increasingly produced and controlled by big companies in a few major countries. These countries became centres of excellence feeding innovation into the international oil industry. The slower continuation of international geographical dispersion of inventors' location (IC) after p2-1 also is an evidence of relative higher difficulty for smaller or new countries (in terms of innovation size) to expand their innovation base. In other words, the scale economy of innovative activities at geographical level after p2-1 appears to increase.

The figures are consistent with the predictions of the hypothesis that the rise of systemic complexity could lower catch-up speed, as entry barriers become higher. Dominance of the systemic complexity of the knowledge base after early p2 could drive mechanisms against dispersion of innovative activities and increase concentration to facilitate exchange and coordination of complex knowledge flows. The findings support that to manage and coordinate complex knowledge bases, cognitive and organizational proximity within different affiliates of the same company (although geographically distributed), is more important than spatial proximity. This is why innovations become more concentrated in terms of the ownership over p3, but continue to disperse geographically in terms of the location of innovation. This 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). A more detailed explanation is presented after analysis of other aspects of geographical patterns of innovation.

7.5.2. Role of new innovator countries

The analysis of concentration of innovative activities illustrates the dynamics of relative distribution of small vs. big innovator countries. However, it does not specifically speak about the extent to which innovators from *new* countries – previously not present - may have a chance of being involved in the innovative activities of a sector. In other words, change in concentration could be the result of either redistribution among existing countries, or emergence of new innovator countries. I address this issue by looking at the relative share of new innovator countries vs. existing ones in different periods, using both location (IC) and ownership (AMIC) country of innovation. Table 7.2 presents the results.

The table shows clearly that the share of the new innovator countries declined over p1, reflecting a decreasing chance for companies from new countries to exploit technological opportunities in this sector. Comparison of these trends with the trend of the role of new innovator companies (table 6.2) suggests that sectoral and geographical patterns do not necessarily follow the same logic. For example, I argued that high opportunity conditions in p1 motivated new companies to enter the industry, as the increasing share of new companies in table 6.2 shows. However, declining share of new countries over p1 shows that the new companies came mostly from existing countries.

In other words, high technological opportunities were mostly to the benefit of companies of active countries already in the system of innovation rather than new countries. This pattern suggests that technological opportunities that brought new entrant companies were largely bounded within already active national territories. In other words, technological opportunities are more *visible* for those already present in the sector who could leverage their benefits. The outsiders share of this expanding pie was decreasing. This observation is consistent with the argument that innovation opportunities are mostly visible to the insiders of existing social networks (Sorenson, 2005; Stuart and Sorenson, 2003). Similarly, the role of new innovator countries also declined over p2 both in terms of innovator location (IC) and ownership (AMICO). Similar explanations may apply.

Table 7-2 The role of new innovator countries over main periods

Country	Inventors country (IC)			Assignees' main invention country (AMIC)		
Sub periods	IFPs Existing Innovator Countries	IPFs New Innovator Countries	Share of new Innovator Countries	IFPs Existing Innovator Countries	IPFs New Innovator Countries	Share of new Innovator Countries
p1-1	2039	122	5.98	2064	74	3.59
p1-2	3136	56	1.79	3132	47	1.5
p2-1	3399	75	2.21	3361	64	1.9
p2-2	3284	32	0.97	3167	10	0.32
p3-1	5667	44	0.78	5323	37	0.7
p3-2	7347	90	1.22	6451	28	0.43

The pattern of change in the share of new innovators countries over p3 is different from two previous periods suggesting a considerable change in the nature of the industry. We observed that the share of new countries over p3 in terms of ownership further declined. However in terms of inventors' location country, the share of new countries increased. This suggests that companies in existing countries performed geographical expansion of their innovative activities into foreign countries. I analyze more this globalization of innovation activities in section 7.7.

Another observation is that on average, the level of new entry reaches its lowest level over p3. Given the high opportunity conditions of this period, the lower level of new entries could at least be partly attributed to increasing systemic complexity. In other words higher cognitive barriers for the companies of new countries prevent them exploiting the emergent opportunities in p3. The systemic nature of innovation dominating in this period implies access to a diverse range of knowledge domains from both different technological domains and different parts of the value chain. This decreases the entry possibility of innovators from new countries which do not have access to this diverse range of knowledge, whether internally or from external sources in the same country. In contrast, it is easier for innovators in existing active countries to get access to diverse knowledge sources which are necessary inputs for systemic innovations. This seems consistent with predictions of the fourth hypothesis, suggesting more limited catch-up opportunities when systemic complexity increases.

7.6. Technological catch-up

In spite of high entry barriers for companies of new countries, there might be some exceptional countries which have managed to escape from their historically low position in the hierarchy of innovators. There might be countries with higher than average growth rates over a long enough period to reduce the gap with leading countries. We define these as *catch- up countries* and propose a methodology to explore them.

7.6.1. Methodology

I employ the Galtonian regression model which regresses the distribution of a normal bivariate variable at two different points of time. This method is often used in order to evaluate the *cumulativeness* and *incremental* change in specialization. It allows statistical examination of both the *degree* and *pattern* of change in the distribution of a variable. 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 became quite popular in the study of cumulative, path dependent and incremental nature of technical change. However, the essence of the method is to explore the convergence vs. divergence processes based on distribution patterns of one variable at two different points of time. As a result, it could be simply applied in other similar contexts, such as the examination of catch-up phenomena in this study. We aim to examine both the *degree* and *pattern* of change in the distribution of innovation among countries between two different points of time. If catch-up processes are effective, statistically significant convergence should be observed among innovation performance of different countries. On the other hand, if strong countries become stronger and weak countries become weaker, we should observe the divergence.

Using this methodology, we set a simple regression model (formula 1) to examine convergence vs. divergence. In this model, the distribution of a variable for the second time period (V_{t2}) is set as the dependent variable while that of the first time period is the independent variable (V_{t1}). The item ε_{t2} is also a stochastic disturbance term which is independent of V_{t1}.

$$V_{t2} = \alpha + \beta.V_{t1} + \varepsilon_{t2} \tag{1}$$

Cumulativeness and incremental nature of change in the variable under consideration are two complementary hypothesises that are usually evaluated with this regression model. The aim is to analyze how the state of distribution in the second instance is influenced by its first instance. Cumulativeness implies the path-dependency in the sense that past situations shape the future positions. Incremental change, on the other hand, postulates the extent to which change is gradual over time vs. being radical and disruptive. Table 7.3 summarizes the ways in which these hypothesises are tested (Cantwell and Santangelo, 2006).

Table 7-3 Statistical test for cumulativeness and incremental change

	Cumulativeness *Mobility effect*	Incremental change *Regression effect*
Hypothesis	H0: β=0 H1: $\beta \neq 0$	H0: β=1 H1: $\beta \neq 1$
corroborate	H0 is rejected and β>0 Equivalence of ρ >0 or • mobility effect as inverse measure of cumulativeness bellow one (1- ρ <1) • **Existence of some degree of cumulativeness**	H0 is rejected and β>1 : **divergence** • negative regression effect (1- β)<0 H0 is rejected and 0<β<1 : **convergence ‘regression towards the mean’** • positive regression effect 0<(1- β)<1 H0 is rejected and β<0 : **overturn** • positive regression effect 1<(1- β)
reject	H0 is not Rejected (β=0) or β<0 Equivalence of ρ <0 or $\rho \cong 0$ • mobility effect as inverse measure of cumulativeness above one (1- ρ)>1 or (1- ρ) $\cong$ 1 • **Randomness**	H0 is not rejected : **persistence** β=1 is equivalence of • no regression effect (1- β)=0

Regarding cumulativeness, we test to reject the hypothesis that H0: $\beta=0$ against the alternative that H1: $\beta\neq0$. The regression coefficient (β) indicates the degree of cumulativeness or correlation of the variable between two periods. This is equivalent to test that H0: $\rho=0$ against the alternative that H1: $\rho\neq0$ when ρ is the correlation coefficient. Accordingly, we evaluate the degree to which different countries have moved their position in the ranking between two periods. If we could reject the hypothesis and ρ is positive, we interpret the existence of some degree of cumulativeness. Otherwise, there is no meaningful relationship between the two distributions and some kind of randomness is perceived. *Mobility effect* is an inverse measure of cumulativeness defined as $(1-\rho)$. If the mobility effect is below one, we could say that there is some degree of cumulativeness. If it is equal or greater than one, there is enough mobility up and down the raking between two periods to interpret the absence of cumulativeness.

Regarding incremental change, we test to reject the hypothesis that H0: $\beta=1$ against the alternative that H1: $\beta\neq1$. If we cannot reject the hypothesis, it means that β is not statistically different from unity. Therefore, the distribution of a countries' innovation performance has not changed on average. In other words, the pattern of distribution has remained stable and *persistent*. If the null hypothesis is rejected and $\beta>1$, there has been a *divergence* process at work. Advantaged countries relatively gained and disadvantaged countries lost their share. On the other hand, if $0<\beta<1$, it implies some gains in disadvantaged countries and some lost share in advantaged countries. In other words, on average the process of *convergence* is at work. It is usually referred to as 'regression towards the mean' (Galton, 1889 cited in Hart (1976)). In the special case of $\beta<0$, the position of advantaged and disadvantaged countries is reversed. This indicates the pattern of *overturn*.

The *Regression effect* is the measure of degree of incremental change, which is defined as $(1-\beta)$. When there is no regression effect $(1-\beta=0)$, it implies relative stability of the position of countries. If some disadvantaged countries gain momentum, there should be some advantaged countries falling behind to create average stability. Therefore the overall effect on the distribution is neutral. When the negative regression effect is observed, the process of incremental change has worked for *divergence*. On the other hand, when regression effect is positive but below one, the process of incremental change has worked in favour of *convergence*.

Overall, we test for β being greater than zero to examine cumulativeness. Cumulativeness and incremental change exist together if β is significantly greater than zero and also significantly less than unity. If β is significantly greater than one (no or negative regression effect), cumulativeness prevails.

Although β is a good measure to capture the *pattern* of change over the time, it is unable to show us alone how the overall *degree* of distribution has changed towards more or less dispersion. In other words, it is argued that positive regression effect *($\beta<1$)* is necessary, but not sufficient condition for higher dispersion. In parallel, negative regression effect *($\beta>1$)* also is not necessary condition for overall increase in concentration of the distribution (Cantwell and Immarino, 2001; Cantwell, 1989).

The relative standard deviation of distributions between two points of time can clarify whether the final distribution is more equally distributed or not. Dalum and Laursen (1998) show that this indicator can be measured according to the flowing equation:

$$\frac{\sigma^2_{V_{t2}}}{\sigma^2_{V_{t1}}} = \frac{\beta^2}{\rho^2} \qquad (2)$$

They argue that if $\beta / \rho = 1$ dispersion of the distribution of the variable has remained unchanged. If $\beta / \rho < 1$ convergence happens: dispersion of the distribution of the variable decreases and the regression effect prevails over the mobility effect. On the other hand if $\beta / \rho > 1$ then the process of concentration happens in total, and dispersion of the distribution becomes less equal. Although the positive regression effect by its own suggests occurrence of convergence due to the proportional movement of categories toward the mean (β<1), mobility effect prevails regression effect because of the proportional change in the position of the categories leading to overall concentration.

This regression model offers practical application for the examination of catch-up processes. In our analysis, $\beta / \rho = 1$ implies persistency of relative position of different countries. If $\beta / \rho < 1$, there has been some catch-up processes reducing the relative gap among different countries. In contrast, β / ρ >1 suggests that average gap among countries have increased. Our evidence does not support the catch-up hypothesis.

7.6.2. Results

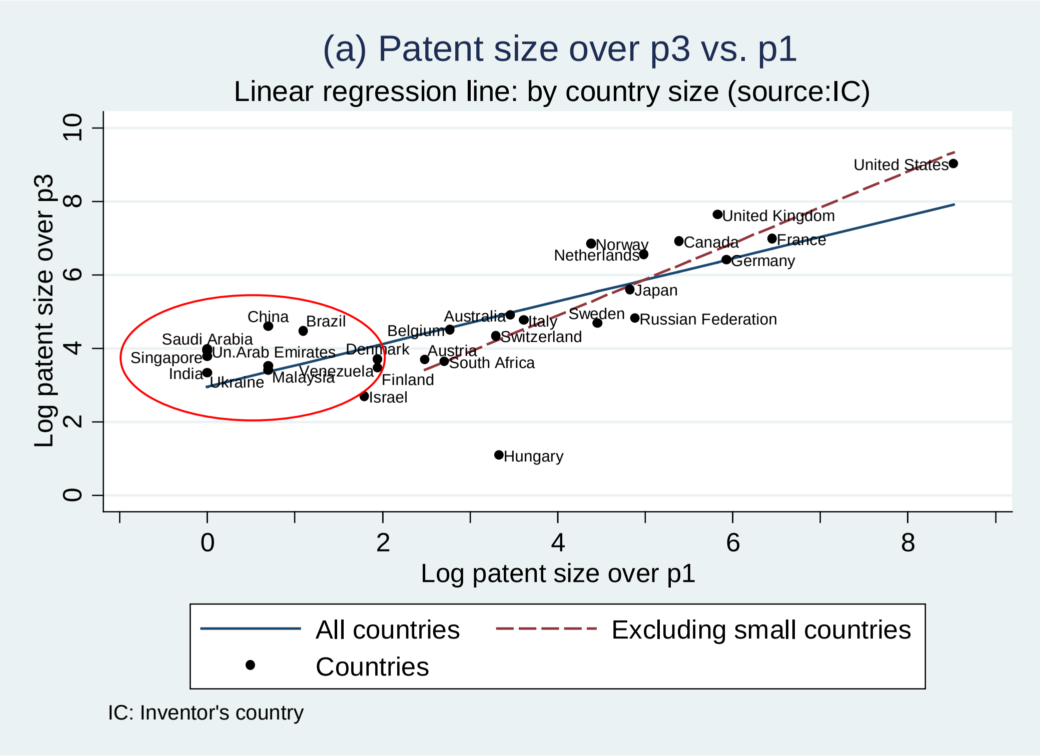
Applying the Galtonian regression model, we can examine whether the innovation performance of the countries converged, diverged, or has been on average stable. That is, whether the innovation gap between countries has grown on average, reduced or remained the same. If the convergence hypothesis is not rejected, we could accept that at least some countries have caught up with leaders and therefore the overall gap among countries partly reduced. I used logarithm of countries' innovation performance in order to normalize the distribution for the linear regression, aggregated over p1 and p3 to examine the catch-up processes between these two periods.

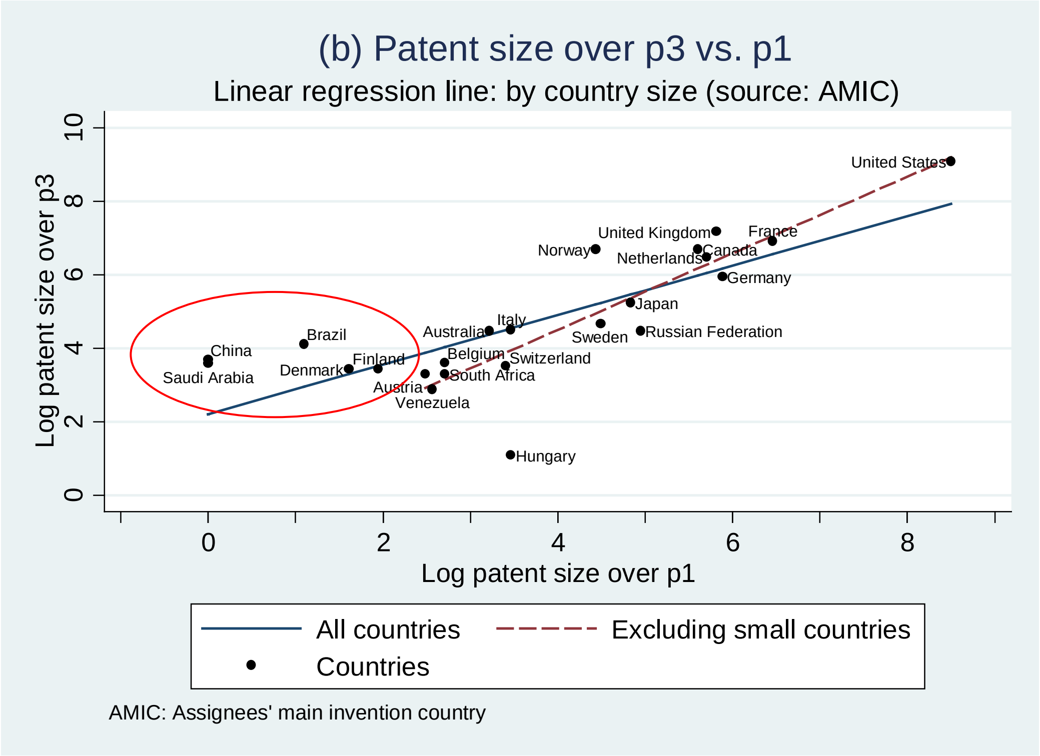
We performed the test using both country of inventors (IC) and owners (AMIC) data and the results are presented in parts (a) and (b) of figure 7.2 respectively. The figure shows the scatter plot and fitted regression line (solid line). The results of the statistical tests are provided in table 7.4. It is evident from the scatter plot that the relationship is relatively linear. Linear regression can be a reliable estimator. The coefficient of the regression model (β) is 0.58 and 0.67 using IC and AMIC respectively, if all countries of the dataset are included in the model.

For the statistical analysis of *cumulativeness*, the hypothesis (H0: β=0) against its alternative (H1: $\beta \neq 0$) is rejected. In other words, we accept that β>0 and therefore cumulativeness of knowledge prevails. The test of *persistence* of the position of countries between two different periods (H0: β=1) does not receive empirical support. Given β<1, our empirical evidence supports the idea that catch-up processes have incrementally taken place between two periods. In other words, we can statistically accept that some countries have managed to *catch up* and eroded the share of some other leading countries which have to some degree *slipped back.*

Although β<1, the visual analysis of the pattern of the position of different countries in the scatter plot raises a complementary question. According to figure 7.2, it seems that a cluster of small innovation size countries on the bottom left of the pattern (within the red circle) have been influential in decreasing the β coefficient from unity and rotating the line upward left.

Figure 7-2 Scatter plot and linear regression of patent size (log): (a) IC; (b) AMIC





In the language of Galtonian' regression model, we accept the hypothesis that countries have experienced 'regression to the mean', but it seems that a large part of regression effect (1- β) is attributable to small countries shown by the red circle (defined heuristically when log patent size<2). This pattern suggests that in the absence of these small innovators with relatively high growth rates, we may not have enough empirical evidence to support that catch-up has indeed taken place. We observe catch-up only because of the rise of share of a few small innovator countries, not because of more equal distribution among all countries.

Table 7-4 Summary of catch-up statistical tests

Countries	β	Sig. test (β=0)	Sig. test (β=1)	ρ	β / ρ
Country source:(IC)					
All	0.58	***	***	0.78	0.75
Non Small	0.98	***		0.83	1.18
Country source:(AMIC)					
All	0.67	***	**	0.79	0.86
Non Small	1.04	***		0.88	1.19

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

IC: Inventors' country

AMIC: Assignee's main invention country

In order to evaluate this idea, I repeated the same tests with these small innovators excluded from the analysis. The dash-line in the figure 7.2 shows the new regression model. In this case β coefficients are no longer statistically different from unity. Therefore the regression effect (1- β) disappears. The interpretation is that the relative share of non-small innovator countries (when small innovator countries are excluded) has not changed overall. In other words our empirical evidence does not support the idea that overall catch-up has taken place *within* non-small innovator countries. This is because the share that the disadvantaged countries gained has been balanced with the lost share of others which have further fallen behind.

As explained previously, change in relative distribution of innovation among countries could be judged on the ground of β / ρ where ρ is the correlation coefficient. The results of β / ρ which are presented in the table 7.4 confirms that if all the countries in the sample are included in the analysis, catch-up phenomena is observable in the sample, because $\beta / \rho < 1$. However among non-small countries this is not the case, as $\beta / \rho > 1$ signalling the increasing gap among big countries.

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 a move towards more unequal dispersion is present from p1 to p3. It means that among non-small innovator countries, the shares gained by some catch-up countries have been compensated by the lost share of others left behind. The overall result is the persistence of the relative position of different countries among non-small innovator countries.

These results provide some insights about catch-up processes. One interpretation is that it is relatively easy to grow innovation, if a country is beginning from a relatively small size. Countries with very small innovation base could simply double their innovative activities and catch up. However among big innovators, catch-up or changing relative position in the ranking is a big challenge. Related to this argument is the emergence of scale and scope economy after a certain threshold. This could stem from the knowledge recombination process, creating increasing returns for investment in knowledge (Antonelli, 2003) when a critical mass is formed. It implies the below a certain level, returns on scale and scope have not an increasing feature and therefore relative change in the position of countries and jumps are possible.

7.6.3. Exploring catch-up countries

We explore the pattern of catch-up countries in this section. Finding these catch-up countries can help us understand how and why catch-up happens in some countries. The difference between the actual patent size of the countries and that estimated by the above model (or residual) 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 others, considering their relative position in the size distribution. In other words, each country is compared with its peers in terms of its size group, not with much bigger or smaller players. This method controls for the effect of size on the possibility and the extent of catch-up processes.

I define the top quartile of the residuals, as the *catch-up range* in order to distinguish more successful countries in building technological capabilities. They are located relatively far from the regression line. All the countries with residuals within the range of the top quartile are considered as catch-up countries. They have on average been able to move more rapidly than other countries and erode some share of leading innovators. Given this definition, the catch-up countries are listed in table 7.5 sorted according to their innovation size. They are listed based on both sources of location of inventors (IC) and owners (AMIC).

This table provides some informative insights about the nature of catch-up in upstream petroleum industry. First, 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. In spite of 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. The number is even less (6) when ownership (AMIC) is considered, compared with the number of catch-up countries based on the location of innovation (IC) which is 8. The disappearance of Canada and United Arab Emirates from the AMIC list means that innovations invented in these countries are largely owned by foreign or non-local companies. In other words, FDI is an important source of innovations where foreign companies have established their R&D facilitates in these countries. If the small players are not considered, only UK, Norway and Canada (just by IC) can be identified as influential technology producers. This means that escaping from the position dictated by historical path, 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, 2005b). The question is what is specific to this industry? And how might this rare number of catch-up countries be explained?

Table 7-5 Catch-up countries in upstream petroleum industries

(a) All countries						
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
		Country source:(AMIC)				
1	**United States**	**4929**	**8925**	**8.50**	**9.10**	**1.16**
2	United Kingdom	334	1316	5.81	7.18	1.05
3	Norway	84	816	4.43	6.70	1.51
4	Brazil	3	62	1.10	4.13	1.17
5	China	0	40	0.00	3.69	1.47
6	Saudi Arabia	0	36	0.00	3.58	1.37

IPF: International patent families

IC: Inventors' country; AMIC: Assignee's main invention country

I showed in chapter 5 that technological opportunities in upstream petroleum should not be a major problem. The high growth rate of innovations since the middle of the 1990s could have potentially motivated companies from many countries to gain benefits. Industry began an innovation boom due to demand for new techniques and, provision and application of a different range of scientific and technological disciplines. But this innovation boom benefited a very limited number of countries. Looking at the mix of the catch-up countries and their historical context can provide some insights. 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 for innovation is an important driver for catch-up. However, this 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 are among advanced industrial nations which have been producing oil for a long time. After US which has been historically the major player in the oil business, UK and Norway are generally industrial advanced countries. They mobilized their technological resources into oil business in order to meet the technological requirements of the North Sea oil, when discovered in the 1960s. Canada is also a major oil producer and also holder of many unconventional reserves which are highly technology demanding. It is interesting that other advanced industrial countries, even technologically very competent ones like Germany could not enjoy the same as UK, Norway and Canada did. This may reflect the location and sector specificity of the knowledge required for technological innovation. The general technological capabilities of advanced industrial countries, though necessary, are not directly applicable. The production knowledge and experience of oil producing countries is an important input into innovation processes, to which non producing countries do not have easy access. This is in line with the idea of the geography of opportunities (Stuart and Sorenson, 2003) which is hidden for outsiders, even if they have the technical competence to exploit it.

However, 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. There is a huge distance between exploration, development and production capabilities; and technological innovation capabilities (Bell and Pavitt 1995; Bell, 2007). Even for countries like China and Brazil with a successful record of technological innovation in other industries, technological catch-up in this industry has been extremely limited, at least in terms of patenting. 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 become marginal innovators, perhaps to meet some of their very specific local needs or technical niches. However, their large scale exploration and production operations are performed largely with foreign produced technology: either imported in the form of capital goods; bought through licensing; or even through turnkey projects which are normally outsourced to affiliates of foreign companies. This is what happens in most oil producing countries which lack indigenous technological capabilities.

7.7. Knowledge base complexity, geography of innovation and catch-up

This section discusses the interpretation of empirical results and their relevance to the dynamics of knowledge base complexity. It argues for the analytical power of the multi-dimensional concept of knowledge base complexity in understanding dynamics of the geography of innovation, because it can compensate for some of the limits of international theory of innovation. It paves the way for a dynamic theory of the geography of complexity.

In terms of technological requirements, today’s upstream projects are very different from some years ago. Not only has the depth and breadth of knowledge increased, accumulated systemic complexity also calls for coordination and integration capabilities which are largely located in companies from just a few advanced industrial countries. The dominance of systemic complexity has increased the need for internal coordination of technological innovation in major innovative companies, although their innovative activities have become geographically more dispersed. This suggests that, to cope with increasing systemic complexity, organizational and cognitive proximity (Boschma, 2005; Boschma and Frenken, 2010) through vertically integrated big companies is not only more important than geographical proximity but is an essential element of complexity management. In other words, company’s vertically integrated internal structures appear as more effective vehicles for transmission and integration of different segments of specialized knowledge from different geographical locations. Not only do they mix and match various internal knowledge sources, they also combine global and local knowledge sources to provide customized efficient solutions.

While they have access to advanced global knowledge sources, they also combine it with local expertise in order to introduce customised services which meet local specificity of demand. This is of particular importance in resources based industries like upstream petroleum industry where location specific characteristics in terms of geological and geophysical conditions must be considered in the design and implementation of projects. There is no one uniform globally applicable design and engineering for upstream projects, although there are some general elements. As a result, global and local knowledge should be viewed as complementary sources, both essential to cope with increasing complexity. This is in fact the task of both types of systems integrators (operators and service companies) to collaborate and cooperate.

7.7.1. Understanding the dynamics of geography of knowledge

A simple classification of different types of innovation and looking at the dynamics of their share over time provides some insights about the dynamics of geography of knowledge. I distinguished between three types of invention in order to capture more directly the divergence between inventors' location and ownership country of patents observed in the figure 7.1. Here are the definitions of these different types of inventions:

- **Local**: Patents which are invented in a country and also owned by companies of that country.
- **Foreign:** Patents which are invented in a country, but assigned to the foreign companies operating in the host country. In other words, these are the result of R&D activities by foreign affiliates in other countries.
- **Collaborative:** Patents which are invented in a country, but co-owned by companies of that country and companies of other countries. Co-ownership implies that companies from both host country (invention country) and other foreign countries have been involved and have collaborated in the invention process.

These definitions are mutually exclusive and each patent can only be classified in one of the above categories. The trends for catch-up countries, US and non-catch-up countries are presented separately in the figure 7.3 to explore the possibility of different behaviours. Non-catch-up countries are defined as 'all other countries', excluding catch-up countries and the US as the leading innovator.

Figure 7-3 Share of different type of inventions according to ownership

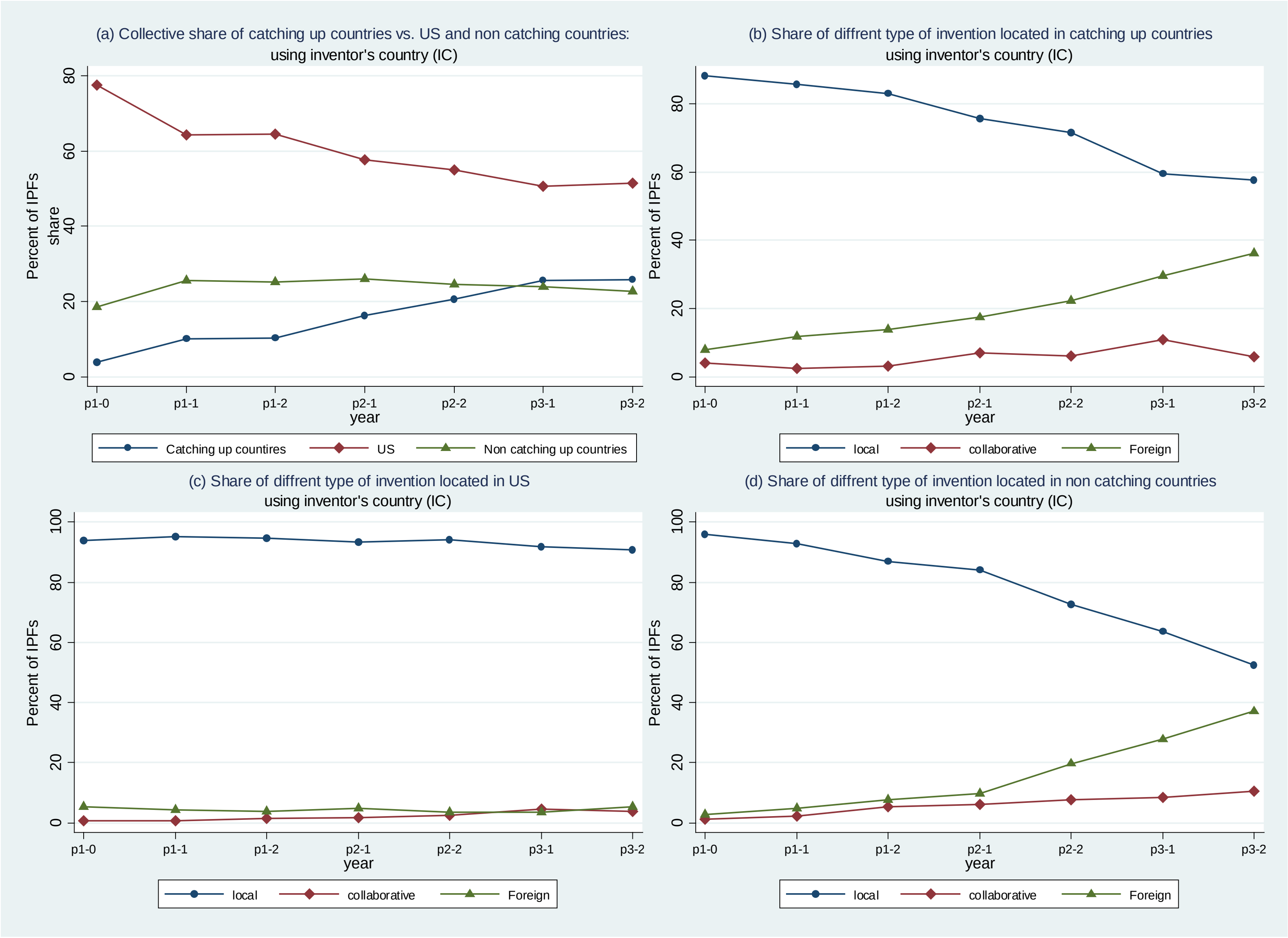


Figure 7.3 (a) shows the share of catch-up countries vs. US and non-catch- up countries, confirming the rising share of catch-up countries particularly between p1 and p3. They collectively overtook non-catch-up countries at the beginning of p3. It also shows that the share of catch-up countries has collectively increased at the expense of decline in the US share. Figure 7.3 (b) and (d) illustrates that the share of foreign inventions has gradually increased from p1 to p2 when its upward trend accelerated. This trend shows that the gap between the share of local and foreign inventions has largely reduced over p3. This implies that the geographical dispersion of innovative activities over this period occurs through increasingly internationalisation of innovative activities of big multi-national companies.

In contrast, the large gap between the share of local and foreign inventions over p1 shows that, in comparison with p3, international geographical dispersion over this period is more attributable to the role of local inventions emerging both within catch-up and non-catch-up countries. The share of collaborative inventions which can be an index for collaborative R&D between local and foreign companies has also increased over time, but less than foreign inventions. Nonetheless, it can be a reflection of the increasing necessity to combine local and global knowledge sources to cope with the increasing systemic complexity of upstream projects.

As expected, patents invented within US have always been dominated by local inventions owned by US companies and this situation has hardly changed over time. This is because of the large size of local inventions compared with collaborative and foreign inventions in the US. It also may reflect the very advanced, large and progressive national system of innovation which creates and utilizes almost all the knowledge required to cope with different types of complexity at different points of time which makes US companies highly competitive. Given the large size and diverse range of innovations produced by leading US companies, we can say that this national system of innovation to a large extent feeds into the global SIS of upstream petroleum industry. As the technological leader of the sector, US reliance on foreign produced knowledge or external collaboration is very marginal.

7.7.2. Is internationalization theory sufficient?

One might argue that the observed trend is simply the same as the well-known trend of *internationalization* of innovation carried out by leading companies in different industries. In this view, internalization of innovation follows internationalization of MNC's production. Indeed, "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). It may have nothing to do with management of systemic complexity of the knowledge base of the industry.

At first glance, the internationalization argument seems applicable to the oil industry. When operating production regions are exhausted and production sites move around the globe, upstream companies need to move their R&D facilities in order to develop demand specific solutions. The land-based character of oil production imposes some limits for achieving scale economies and shapes the nature of technological developments in upstream industry (Prudham, 2005). Economies of scope have become more relevant in the upstream end of the value chain. Firms need to "develop technological solutions capable of addressing the *heterogeneity* of exploration conditions and reservoir types" (Bridge, 2008, p. 407, emphasis added). This localization is not limited to technical knowledge but extends to market, financial, social, political, environmental and organizational knowledge (Bridge and Wood, 2005). If the upstream companies are to stay competitive, they need to geographically disperse their knowledge generating units to cope with the strong local nature of the industry.

The argument seems reasonable and valid, but does not sufficiently explain at least three aspects of dynamics of the geographical pattern of innovation and more importantly the mix of catch-up countries. The first aspect is the timing of internationalization. The oil industry has been internationalized from the beginning of the twentieth century. Yet, internalization of *innovation* is rather a much more recent phenomenon in this industry, as the trend of foreign patents in figure 7.3 suggests.

The second aspect is that overall catch-up processes stopped in p3, and the trend of geographical dispersion of innovation visibly slowed down, when systemic complexity increased. The gradual share transfer from US to a few catch-up countries stopped and was even somehow reversed in p3. US began to regain its share and catch-up countries could not increase their share in p3 (figure 7.3 a). Related to this issue is the slow down in the trend of geographical dispersion of innovations in terms of inventors' country (IC) after p2 and more importantly its discontinuation over p3, as shown by figure 7.1.

The third noticeable aspect is the divergence of concentration trends between assignee and inventors' country after p2 (figure 7.1). Although internalization theory proposes a higher dispersion of innovative activities over time, it does not provide an explicit explanation about the conditions under which change in the location of innovation happens with or without change in ownership structure.

7.7.3. How does complexity perspective help?

The dynamic concept of three-dimensional complexity could shed some light on these aspects and offer additional analytical value. To begin with the third aspect, I explained that 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. Based on foreign patenting trends in the figure 7.3, there was a very limited internationalization in p1. Therefore, a large part of the more equal geographical dispersion of innovation (figure 7.1) in this period should be attributed to local innovations in catch-up countries. This is compatible with the Schumpeter Mark I nature of this period when cognitive barriers to entry were relatively low.

In contrast, 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. Diffusion of ICT in all sectors of the economy including upstream sector also could have facilitated this internal knowledge coordination capability within multinational companies over large distances (Santangelo, 2001).

When systemic complexity increases, the leading companies in the sector which largely originate from industrial advanced countries are better placed than other companies. They have access to a diverse range of geographically distributed knowledge. They also benefit from internal integration capability over large distances which enables them to "go global" (Bridge and Wood, 2005). Cantwell (1995) uses the term new "globalization of technology" to describe this new recent situation in contrast with the earlier 'internationalization' hypothesis. However he does not talk directly about the role of systemic complexity. He explains that these companies enjoy benefits from economies of scale, scope and geographical agglomeration all at the same time in their knowledge production activities. This feature enables big multinational companies to overcome systemic complexities arising in the sector and implement locally customised operations using globally available specialized advanced knowledge.

This distinction between *internalization* and *globalization* is intentional and in line with Cantwell's (1995) terminology, as explained above. This is to emphasise not only that the *extent* of foreign patenting has been different over the latest period (p3) compared to the earlier periods; its *aim* and *nature* also have been different. In fact this should reflect the particular type of knowledge base complexity to which companies were facing.

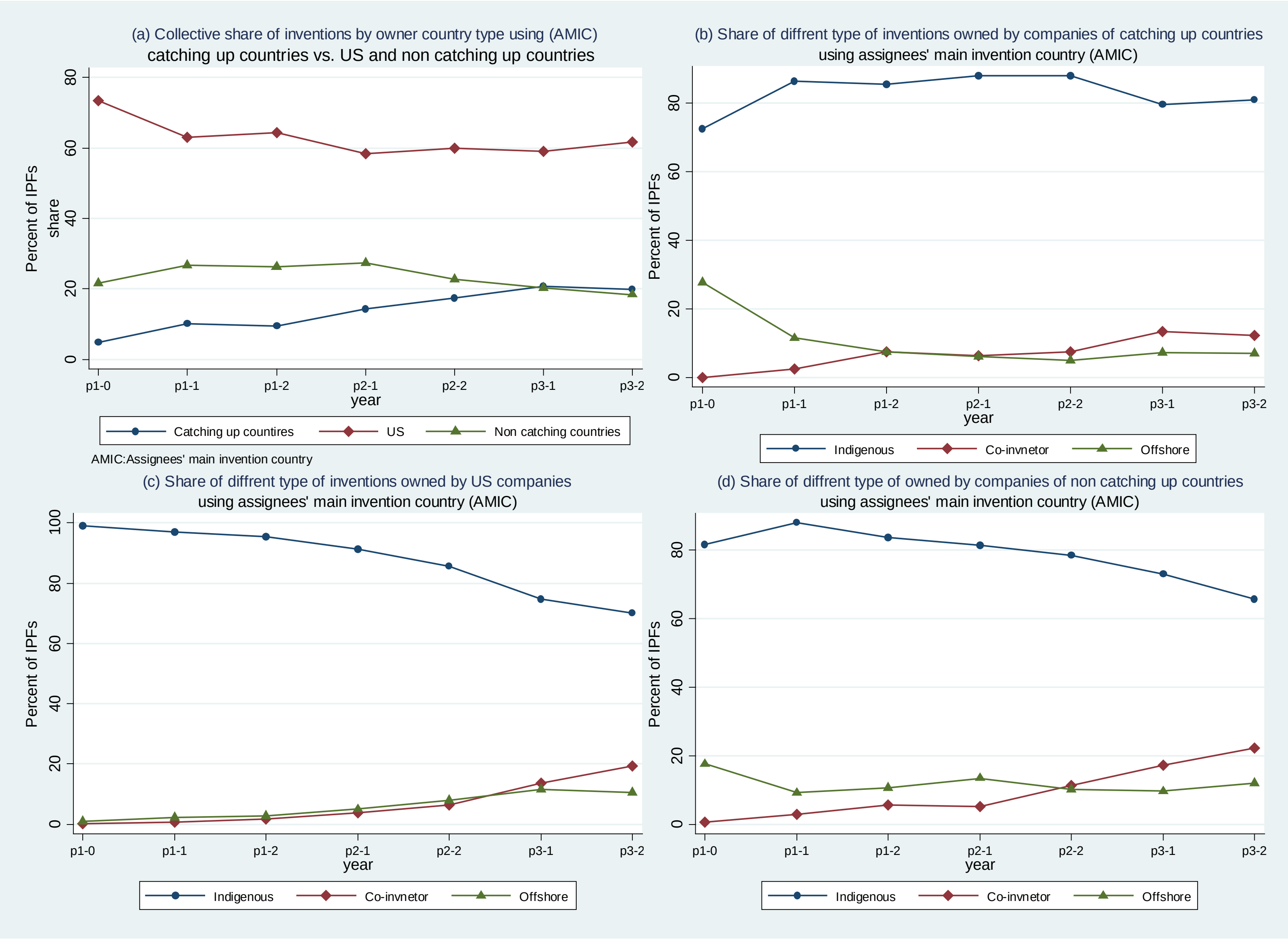
Companies follow an internationalization of innovation in order to produce different complementary kinds of knowledge to customize their products or services for local peculiarities. This is more about the breadth and depth complexity needed, as they extend their home grown knowledge. However, according 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.

The key difference is that there is no intensive knowledge integration exercise between different geographical locations, when the aim is *internationalisation*. However, *globalization* of innovation involves intensive integration and exchange of geographically distributed knowledge sources in order to cope with increasing systemic complexity. Cantwell (1995) showed this issue by tracing the different technological specialization of innovation activities at home and abroad in leading companies over time. I developed a different and more *direct* method to trace the intensity of knowledge flows between home and abroad in the innovation processes. A typology of inventions is introduced in order to recognize the dominant strategy of the companies over different periods:

- **Indigenous inventions:** patents owned by companies of each country which is also invented due to research in that country.
- **Offshore inventions:** patents owned by companies of each country which is invented due to research carried out abroad with no inventor from the home country.
- **Co-inventor inventions:** 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.

These definitions are mutually exclusive and each patent can only be classified in one category. The share of each type of patent over time is presented in figure 7.4 for different groups of countries separately. The share of these countries in innovative activities (a) is also presented. Consistently, the share of co-inventor patents in all three groups of countries overtakes the share of offshore patents over p3 while p1 witnessed a reverse situation. As predicted, the intensity of knowledge exchange and integration exercises between innovators of different locations has increased over time. This is a reflection of the shift from dominance of internationalization in p1 to globalization in p3. Inventors of the companies at home and abroad have been working relatively independent of each other in p1, as the lower percentage of co-patenting suggests. Although the share of foreign patenting has been rising (figure 7.3), the co-invention or cooperation between a parent company with its affiliate or with other foreign companies operating abroad is a more recent phenomena.

Figure 7-4 Share of different type of inventions in terms of inventors’ location



AMIC:Assignees' main invention country

This confirms the fact that both the *level* and *nature* of foreign patenting have changed over time, consistent with dynamics of knowledge base complexity.

In sum, the evidence presented shows that the dynamics of knowledge base complexity is helpful to explain diverging trends of geographical concentration of innovation when measured on the base of inventor (IC) and owner (AMIC) country (figure 7.1). It was shown that the change in the aim and nature of foreign patenting from offshore type in earlier periods to co-invention in p3 is associated with a shift from breadth to systemic complexity. The rise of systemic complexity offers unique advantages to big multi-national companies in knowledge generation processes, because they can benefit from economy of scale, scope and agglomeration across the globe at the same time (Cantwell, 1995). While the ownership share of big multi-nationals gains momentum, they geographically disperse the location of their innovative activities to get access to specialized knowledge in different centres of excellence. As a result, these companies go well ahead of other more local companies in less advanced countries giving raise to divergence between two geographical trends. This is not driven by change in the location of production sites, but by search for advanced knowledge in different centres of excellence to be integrated in companies’ knowledge base.

However, before that period, international geographical dispersion was driven by the combination of the rise of local innovations by home companies of catch-up countries (figure 7.3) and some offshore inventions by multi-national companies (Figure 7.4). Both are compatible with dominance of breadth complexity and less systemic complexity in that period. As a result, the trend of geographical dispersion in p1 (figure 7.1) both in terms of inventor and owner country are closer to each other. We observed that the internationalization theory of innovation is not adequate to explain the diverging geographical trends between the location and ownership of innovation trends in p3. In contrast, increasing systemic complexity, which is also consistent with globalization theory of innovation, is better equipped to explain the observed diverging pattern.

So far, the third unexplained aspect of dynamics of geography of innovation in the sector which mentioned in previous section is addressed. It is argued that the dynamics of knowledge base complexity could clarify this unexplained geographical aspect.

The other aspects of dynamics of geography innovation can also be explained with reference to the dynamics of knowledge base complexity. With regard to the second aspect, increasing systemic complexity in p3 can explain the discontinuities observed in the rising trend of the share of catch-up countries and recovery of American hegemony in the sector (figure 7.4 a). Companies from other countries than American companies are in a worse position to cope with the systemic complexity of the industry over p3. US companies have been more successful than others in managing and benefiting from systemic complexity, because of their access to a different range of knowledge segments at both local and global level. On the one hand, they originate from a rich national system of innovation which generates diverse ranges of knowledge. On the other hand their globalization offers access to the variety of local knowledge worldwide.

Their system integration capabilities also support knowledge generation through recombination of local and global knowledge processes. These conditions enable them to exercise better than others economy of scale, scope and agglomeration at the same time, which explains their higher growth rates over p3. Although p3 is a special ceremony for the big companies to embrace increasing systemic complexity, the biggest of the big companies from US gain more than relatively smaller big companies from other territories (UK, Norway, Canada). The stalled international geographical dispersion trend over p3 is also due to the re-concentration of innovation both within the US as a location of innovation and as the origin of big innovator companies (figure 7.1).

The dynamic concept of three-dimensional complexity can also address the first aspect mentioned above with regard to the mismatch between timing of internalization of oil production and innovation in the sector. Internationalization theory predicts co-occurrence of internationalization of production and innovation which does not apply to this sector. Complexity perspective on the other hand suggests the degree and type of international innovative activities by leading companies develop in accordance with the degree and type of complexity. We observed that internalization of innovation is associated with increasing breadth complexity, while increasing systemic complexity is more consistent with the new globalization of innovation.

Although oil production has been very international since the early twentieth century, it seems that internationalization of innovation is a much more recent event in the sector. As figure 7.3 suggests, foreign patenting begins in the early 1970s. Again, the dynamic complexity perspective offers insights to understand why doing R&D abroad was not critical before. The answer is that localized R&D was not very critical because of low levels of complexity in the upstream projects. Cheap and easily accessible oil reservoirs from major producing fields at that time did not need sophisticated technology and local customization. Although local specifity has always been a feature of oil industry, it seems that standard and generally produced tools for the upstream projects were efficient enough for simpler and somehow standard projects of that time. Therefore, foreign R&D activities were not seen very fundamental and important for competitiveness. We can label this period as the time of ‘non- internationalization’ of innovation when most innovations were of a local type with the dominance of US in knowledge generation (see trend of US share in figure 7.4 a).

To sum up, the dynamics of complexity argument appears convincing to explain the changing dynamics of geography of innovation. We observe ‘non-internalization’ of innovation before 1970s when US had technological hegemony and the knowledge base of the sector was relatively simple. The 1970s and 1980s is the period of catch-up and ‘internationalization’ of innovation which is consistent with increasing breadth complexity. The increasing systemic knowledge base complexity since the mid-1990s also triggered the transformation to ‘globalization’ of innovation when catch-processes stopped and US exercised a new technological hegemony.

The dynamic and three-dimensional complexity not only offers analytical value to understand the dynamics of geography of innovation, it also provides some insights for catch-up theories. The mix and dynamics of share of catch-up countries suggest that the catch-up process is not fully demand driven, but also strongly conditioned to the pre-existence of some local innovation capabilities on the supply side. These local capabilities could attract foreign companies in one hand and support local companies when they face different types of complexity. Lack of local capabilities can explain why many countries are not able to catch-up and take advantage of the flourishing technological opportunities in the sector. Without these local capabilities, companies are not able to deal with breadth and depth complexity, let alone the extra challenge of systemic complexity. Accordingly we could understand why catch-up processes in 1970s and 1980s were led by a few advanced industrial oil producing countries (UK, Norway, Canada). We can also understand why even these marginal catch-up efforts stopped and international geographical pattern re-concentrated when systemic complexity increased in the 1990s.

7.8. Conclusion

This chapter 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. The case of upstream petroleum industry offers a rich and unique opportunity to combine both dynamics of knowledge base complexity and interesting dynamics in geographical patterns of innovation. Putting the dynamic and three-dimensional perspective of the knowledge base complexity at the centre of analysis, this chapter provides three main contributions to the field of geography of knowledge base complexity.

First, at the conceptual level, it removes some of the ambiguities and inconsistencies in the literature with regard to the geographical impacts of complexity. The second contribution is of methodological type. A set of measures and statistical tests are combined in order to describe the dynamics of geography of innovation and their association with the dynamics of knowledge base complexity, as formulated in the fourth hypothesis of this PhD research. Third, application of the suggested methodology provides broad empirical support for this hypothesis, while offering some analytical insights with regard to the dynamics of geographical patterns of innovation and catch-up processes. This is a step forward towards a dynamic theory of the geography of knowledge base complexity, in which the geographical dynamics of innovation progress in accordance with the changing nature of knowledge base complexity.

At a conceptual level, we argue 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 and depth 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. Some of the ambiguities and inconsistencies in the literature come from a lack of clear distinction between these dimensions and their various impacts.

Using a dynamic and three-dimensional perspective to knowledge base complexity, we formulated the fourth hypothesis (H4) of this research. We expect easier new entries and more opportunities for latecomer catch-up, and therefore more rapid geographical dispersion, when systemic complexity is low and breadth and depth complexity are dominant. In contrast, increasing systemic complexity implies higher barriers to entry. Therefore it provides fewer catch-up opportunities and we expect slower geographical dispersion or even moves towards higher geographical concentration.

We found empirical evidence to support the 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 contrast, increasing systemic complexity slows down geographical dispersion. It seems that this condition is more in favour of bigger innovator countries and the companies originate there. However the analysis also shows that those wider opportunities in the conditions of breadth complexity are not open equally to everybody. The 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 realize these innovation opportunities and exploit them at a global level. Without these preconditions, it is very unlikely that companies from latecomer countries in the sector will overcome the cognitive barrier. Many oil producing countries gain higher positions in the technological hierarchy of the petroleum industry. 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.

In addition, the empirical results offer some theoretical insights about the dynamics of geographical patterns of innovation. I argue that the standard internationalization theory of innovation is not sufficient to explain three aspects of geographical dynamics. These are: the temporal mismatch between the international geography of oil production and innovation; the slow down and eventual halt of geographical dispersion of the upstream petroleum industry in later periods; and, divergence of geographical dispersion trends when measured with base on inventors and assignee' countries. These three aspects of the dynamics of geographical patterns of innovation are better understood in the light of the dynamic and three-dimensional concept of knowledge base complexity. We found that observed dynamics in geographical patterns of innovation progress in accordance with the dynamics of knowledge base complexity. The knowledge base of the industry goes from the state of relative simplicity, to the dominance of breadth, and then systemic complexity. In parallel, the geographical dynamics of innovation move from relative non-internationalization to internationalization and finally to a new globalization of innovation. These findings offer valuable insights for the development of a dynamic theory of the geography of knowledge base complexity, as an attractive area for further research.

8. Chapter 8: Summary and conclusions

8.1. Introduction

This chapter summarises the findings of this research, linking them together and locating them within previous research on the 'knowledge' and 'learning' approaches to resource based development. The chapter also discusses the policy implications of the findings, describes the limitations of the research and provides some suggestions for further research in the field.

We explained that this thesis is situated between two gaps. We found that there is a lack of adequate understanding about the dynamics of the knowledge base in resource based industries. On the other hand, the dynamics of knowledge base complexity is a relatively neglected area in sectoral innovation systems approaches. Although mentioned as an important element of technological regimes, it has not been well articulated. Looking at the dynamics of knowledge base complexity in the upstream petroleum industry, this thesis aimed to address both gaps. On the one hand, it increases our understanding of the dynamics of knowledge base complexity and its role in transformation of sectoral innovation systems. On the other, it feeds into the natural resource based development literature, providing a deeper picture of the opportunities and challenges involved in these sectors regarding the underlying knowledge and innovation processes.

We review the research objectives and questions in section 8.2. The overarching research question which guided this research and the three operational research questions of this thesis are addressed. Section 8.3 combines and summarizes the findings and explains the main contributions of the thesis. Section 8.4 discusses the policy implications and the practical lessons which can be drawn from the findings. The limitations of the research and suggestions for future research are discussed in section 8.5.

8.2. Research objectives and questions

We explained that dominant approaches in the resource based development literature tend to provide an exogenous and static picture of natural resource industries, where the role of knowledge and innovation is relatively neglected (Andersen, 2012). This conventional 'resource curse' view (Stevens and Dietsche, 2008) tends to conceptualize resource based industries as the sectors with 'inherently' limited innovation and developmental capacity (Lorentzen, 2008a). Such weaknesses, along with recent changes in the global economy (Morris et al., 2011), have pushed researchers to look for alternative analytical approaches. Referring to some common elements in this emerging research agenda, they are labelled as a ‘knowledge’ (Lorentzen, 2008a) or ‘learning’ (Wright, 2001; Andersen, 2012) approach to resource based development. According to these new approaches, the performance and contribution of natural resource sectors to the economy is not something given, but a function of learning, innovation and knowledge accumulation in society.

Our observation confirms the richness of technological opportunities in the petroleum industry and its resurgence since the mid-1990s. Nonetheless, it is clear that many oil producing countries have not been able to harness these opportunities. In other words, many still operate under a production-oriented paradigm, while innovations are concentrated only in a few industrial countries.

Accordingly, the overarching question which informed my doctoral research was:

Can the new ‘learning’ approaches to resource based industries provide a complementary explanation for the oil producing countries’ struggle to enjoy the innovation opportunities emerged in upstream petroleum industry, given the limitations of the conventional ‘resource curse’ view?

It is explained that there are basically two ways to answer the overacting question. One way is to focus on the context of individual countries and find the internal and structural factors which stifle or at least do not support learning processes. This approach tends to look at poor policies or unsupportive institutions. The second way is to look at the characteristics of what needs to be learned or the *nature of knowledge.* Some kinds of knowledge can be easily obtained. However, there are other kinds which are difficult to learn. The aircraft industry is an example with difficult to learn knowledge. Although the aircraft industry has been a commercial industry for a long time, still few countries have the technological capability for production and innovation. Obviously, the two ways to answer the overarching question are complementary and do not exclude each other. We follow the second route to answer our overarching research questions, as it has been less addressed in previous research.

In other words, we are more interested to explore the ‘cognitive’ barriers for new participants to enter in the innovation processes. The intuitive hypothetical answer is that increasing technological complexity has played an important role to prevent latecomer countries from knowledge base development in the upstream petroleum industry. This broad hypothesis translated to three main research questions which guided the current thesis:

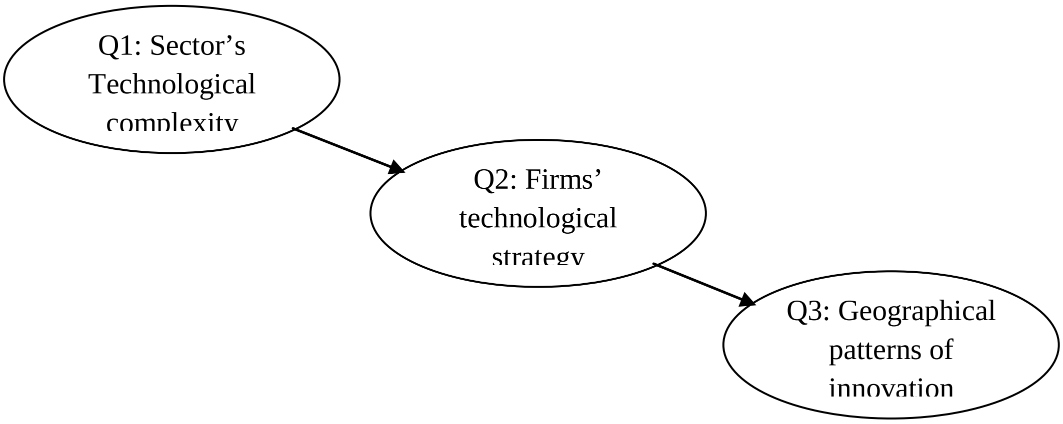
1- How has technological complexity in the upstream petroleum industry evolved over time?

2- How is the governance system of sectoral knowledge base adapted to the dynamics of technological complexity? And how have different firms responded or adjusted to the dynamics of technological complexity?

3- What are the implications of dynamics of technological complexity for the international geography of innovation and catch-up processes?

To address the first question I explored whether the patent data support the idea that upstream petroleum industry has become technologically more complex. For the second question I investigated how did firms’ technological and innovative behaviour change or adjust according to the dynamics of technological complexity. For the third question, I explored how change in the technological complexity affected the dynamics of geography of knowledge and innovation at an international level and shape catch-up possibilities. The second question is a mediatory question, linking the first and third question through exploration of firms’ technological behaviour. This is based on the belief that the dynamics of complexity can only affect the geography of innovation and knowledge through firms' strategy towards knowledge and organization of innovation (figure 8.1). Firms decide how and where to perform their innovative activities. As a result, we are unable to understand deeply the impact of technological complexity on the geography of innovation, unless we understand the impact of complexity on firms' innovative behaviour.

Figure 8-1 Relationships between research questions



In order to answer these questions, this research presents three main contributions. At the theoretical level, we propose a dynamic and three-dimensional perspective to knowledge base complexity. We argue that this view offers analytical values to explain patterns of innovation at sectoral, organizational and geographical levels. In addition, we clarify some of the conceptual ambiguities and theoretical inconsistencies about the impact of technological complexity in the literature. The second contribution is methodological where we develop a quantitative methodology to capture the dynamics of knowledge base complexity and examine its association with patterns of innovation. The third contribution was empirical. The application of the suggested methodology in a resource based sector is an empirical extension of studies of sectoral knowledge bases which previously were concerned with new modern sectors neglecting the importance of established industries.

8.3. Summary of the findings

In this section, I review the hypotheses developed in connection with the three research questions and present the main empirical findings of this thesis. I also present the theoretical implications of empirical findings.

The sectoral innovation systems approach is introduced as the broad relevant analytical framework. We argued that application of this approach in conjunction with the industry architecture framework provides new insights about the dynamics and transformation of the upstream petroleum industry. This is because this approach puts knowledge and technological regimes at the centre of analysis and systematically analyzes the role of various interacting factors in the dynamics of innovation. In addition, it avoids sectoral generalizations and puts the emphasis on sector-specific analysis. As a result, we can provide a more comprehensive and 'history friendly' (Malerba, et al., 1999) model of industry evolution.

We found that the upstream petroleum industry has been a very dynamic sector since 1970 with major transformations over time. Three distinctive phases are explored over which the configuration and performance of the sector has changed. The analysis of patent data shows that technological opportunities in the first period (from early 1970s to the mid-1980s) was high, as reflected in a rising innovation trend. While the innovation trend in the second period (from mid-1980s to mid-1990s) experienced a gradual negative trend, the rate of innovation growth increased sharply after the mid-1990s. As a result, the third period of the sector is characterized as a period of technological explosion. The main driver of transition from the first to second period was the collapse of oil prices which reduced financial resources and contracted the demand for innovation. In addition, the deleterious impact of vertical disintegration or divesture on innovation stimulated by low oil prices has been supported in the literature (Teece and Armour, 1976). In contrast, expansion of a ‘qualitatively’ different demand for innovation in complex upstream projects in harsh and less accessible environments was the major factor behind transition from the second to the third period. Moreover, vertical integration strategies had positive impacts on the innovation performance of the sector.

A related theoretical conclusion is that standard application of conventional industry lifecycle (Abernathy and Utterback, 1978) is not able to explain innovation in an industry as mature as the upstream petroleum sector. Given the simplistic view of this model, more systemic approaches such as SIS can provide deeper insights about the innovation divers, industrial dynamics and its structural consequences. Analysis of upstream SIS illustrates the sector as a highly dynamic and innovative, particularly in the most recent period. It is shown that major disciplines such as mechanics, chemistry, physics and geophysics, electronics and even biology and biotechnology all contributed to the knowledge base of the sector. In addition, the upstream petroleum knowledge base has considerable overlaps with other industries such as mining, polymer and plastics, instrumentation, electrical and communication, and the chemicals industry. My analysis of the main patentees also confirms that the upstream industry is an active innovator from insider participants. As a result viewing it as only a passive receiver of innovation from other sectors is wrong. A different range of operators, integrated service companies and specialized firms as well as non-firm organizations like public R&D institutes and universities, are all involved in the innovation processes. Integrated service companies are positioned at the top of the list of innovators. We dig more into the dynamics and transformation of upstream petroleum industry through the analysis of dynamics of technological complexity and its role in the industry evolution and patterns of innovation.

8.3.1. Dynamics of knowledge base complexity

In response to the first research question, we began with the underlying hypothesis that:

Hypotheses 1: Upstream petroleum industry has gradually moved towards higher degrees of technological complexity.

This hypothesis is empirically supported. However a more subtle and articulated meaning of complexity emerged in this study. Using background research on the concept of complexity, we proposed a dynamic and three-dimensional perspective capturing three different aspects of evolving knowledge base complexity. We found that the dominant type of complexity in different periods may change. In the upstream petroleum industry, depth complexity is shown as a pervasive aspect of complexity which often increases over time. Breadth complexity rises in the early phases while more recently we have the period of increasing systemic complexity.

Drawing from the dynamic and three-dimensional perspective to knowledge base complexity conceptual contribution of this thesis, we presented a more comprehensive and precise picture of the industry lifecycle in the upstream petroleum industry. In other words, a ‘knowledge based perspective’ to industry lifecycle proved a useful analytical tool and more relevant than traditional indicators like firm size and number, in order to study industrial dynamics in the era of knowledge based economies. It is good to recall the fact that technological opportunities can be very high in an old and mature industry in the conventional sense; and even become greater than in the early stages of the industry. Therefore, the rate of innovation and degree of technological opportunities is only a very partial indicator to distinguish the main phases of industry.

This study is an extension of recent research on the lifecycle of knowledge intensive industries (Grebel et al., 2006; Krafft, et al, 2009 & 2011), illustrating the usefulness of the approach even in traditional established industries. This suggests that knowledge economy is not crystallized in particular sectors, but is a widespread phenomenon in all sectors of the economy. The suggestion of a three-dimensional conception of complexity, and more importantly my attempt to measure them over time, was an important step forward to address this gap in the literature

My data appear to provide convincing evidence to distinguish between two main cycles of upstream petroleum industry and a transition phase between the two, according to the dynamics of complexity and structure of knowledge base. According to evidence provided, we could label them as ‘fluidity’, ‘transition’ and ‘maturity’ phases as an analogy. This three phases almost correspond to the main three periods explored, based on the technological opportunities of the sector. But we need to be careful as the meaning assigned to these phases is very different to the conventional (Abernathy and Utterback, 1978) or ‘pre-historic’ perspective. The focus here is not on the horizontal structure of the industry, but on the structure of the ‘knowledge base’.

As the analysis of dynamics of knowledge base complexity shows, the period before the early parts of period 2 (p2) can be described as the period of dominance of breadth complexity associated with random search and exploration strategy. Knowledge structure is relatively shaky and changing. These features imply *narrow cumulativeness* for this period. New fields are continuously added to the knowledge base of the sector, but cross fertilizations and linkages lag and are limited. In contrast, the period after the early second period (p2) is best described as the period of increasing systemic complexity, where recombination and cross-fertilizations within defined trajectories become dominant. This characterizes the period of organized search and exploitation of the technologies explored in the previous phase. The result is a relatively stable knowledge structure and *wide cumulativeness* which stem from complementarities and cross fertilizations.

8.3.2. Governance of evolving knowledge base complexity

Given the three-dimensional picture drawn from the evolution of knowledge base complexity in the upstream petroleum industry, we also expect the knowledge governance system to change over time. Two related and complementary hypotheses are proposed based on two different strands of the literature, in order to respond to the second research question of the thesis. Examination of these two related and complementary hypotheses sheds light on the ways in which the changing nature of the sectoral knowledge base affects and shapes the relative role of different participants in the knowledge environment. The main concern was to explain the dynamics of *sectoral governance of knowledge* as a function of evolving knowledge base complexity.

It was explained that the question of knowledge governance in different sectors has been the subject of at least two relatively separate research programs which look at different, yet complementary aspects. First is the Schumpeterian tradition which tends to focus on the relative role of *small vs. big* and *new vs. incumbent* firms with regard to their contribution in the innovation processes and the development of sectoral knowledge base. According to this tradition, we examined the second hypothesis of this thesis.

Hypothesis 2: we expect the sector to move towards Schumpeter Mark I over p1 when breadth complexity is increasing and systemic complexity is decreasing. We also expect a shift towards Schumpeter Mark II after early p2 when systemic complexity is increasing and breadth complexity declines.

The second tradition tends to look at the *division of knowledge* between different players and their particular *functions* in the governance of the sectoral knowledge base. In other words, the role of different actors is explored collectively and systematically to analyze the dynamics of *direction* (specialization vs.

diversification) of their innovation strategy. According to this tradition, the third hypothesis claims that:

Hypothesis 3: we expect most of the agents to follow a technological specialization strategy over p1 when breadth complexity is increasing and systemic complexity is decreasing. We also expect some of the agents which become system integrators to shift towards a technological diversification strategy after early p2 when systemic complexity is increasing and breadth complexity declines.

It is clear that both research programs highlight different aspects of the knowledge governance and are complementary to each other. However, the existence of one common gap in both research traditions was an academic opportunity to remove the distinction between them and offer novel contributions. The dominance of a *static* mode of analysis has narrowed the scope of questions they can answer, although there is no inherent conceptual and theoretical limit for their extension to a more *dynamic* mode of analysis. The introduction of a dynamic and three-dimensional perspective to knowledge base complexity provides a unique opportunity to offer dynamism to both approaches and reduce the distinction between their visions, based on the shared concepts incorporated in them. The case of upstream petroleum industry offered a unique opportunity for empirical examination of this suggestion.

We found empirical evidence in support of both hypotheses. In terms of H2, we found that Schumpeterian patterns of innovation in the upstream petroleum industry shifted from mode I in earlier periods to what resembles mode II in more recent times. This is explained with the dominance of breadth complexity in the earlier periods which later converted to increasing systemic complexity in more recent times.

As the by-product of examination of this hypothesis, a broader theoretical contribution to the Schumpeterian approach is suggested. We proposed a dynamic theoretical framework in which the dynamics of Schumpeterian patterns of innovation can be explained in terms of the combination of two dimensions of technological regimes. It was shown that *knowledge base complexity*, if combined with *technological opportunities*, could convincingly explain the dynamics of Schumpeterian patterns both in terms of *degree* and *mode*. While the shift in complexity type from breadth to systemic can alter the Schumpeterian *mode*, a change in opportunities tends to affect the *degree* of existing mode (weaken or strengthen) without altering it. The combinations of these two dimensions of technological regimes provide a basis for a dynamic theory of knowledge governance.

The analysis of upstream petroleum industry provides empirical support for this *Schumpeterian* version of the dynamic theory of knowledge governance. We showed that small and new innovators can exploit increasing technological opportunities most when knowledge base complexity is predominantly of the breadth type and systemic complexity is low. This most resembles the features of Schumpeter Mark I. In contrast, when the systemic complexity increases in the sector, the rise of technological opportunities is relatively more beneficial to large and incumbent companies. This situation characterizes the Schumpeter Mark II mode. As a result, the transformation of Schumpeterian pattern of innovation from mode I to mode II can be understood with reference to the increasing systemic complexity of the knowledge base. This analysis shows that high technological opportunities can reduce the gap between small and big innovators only when systemic complexity is low (Schumpeter Mark I). However, if systemic complexity dominates the sector (Schumpeter Mark II), high technological opportunities are most likely to widen the gap between small and big innovators. This argument similarly applies to new vs. incumbent innovators.

The third hypothesis of the PhD is also supported by empirical evidence. It is shown that before early p2 when breadth complexity is increasing and systemic complexity is decreasing; all three types of actors take a *specialized growth innovation strategy*. However over p2 and p3 when systemic complexity increases sharply, Integrated Service Companies emerge as the new systems integrators of the sector with aggressive *diversified growth innovation strategy* to cope with this excessive systemic knowledge base complexity. In other words, when interactions and interrelatedness between different technological domains are intensified, market based decentralized mechanism may not be sufficient for governance of systemic complexity. As a result vertically integrated systems integrators manage this type of complexity via their internal innovation network.

In addition, it is shown that there is no *unified theory* which can consistently explain two novel aspects of the dynamics of the knowledge governance explored in the upstream petroleum industry. The first is the *full cycle* of disintegration and back to what I characterized as neo-integration. The second novel aspect is the emergence of integrated service companies as new system integrators and their *forward integration* strategy. We observed that they became leading innovators following *aggressive diversified growth innovation strategy*. These two novel aspects can be explained according to the dynamics of knowledge base complexity embodied in a co-evolutionary framework. The framework originally was proposed (Jacobides and Winter, 2005) to explain change in the vertical scope of production and division of labour among different firms. I suggest a similar application in the knowledge domain to explain the dynamics of division of knowledge among firms, and governance of the sectoral knowledge base.

This framework combines transaction costs as a partial endogenous variable and firms' capabilities in order to explain the dynamics of governance structures. A dynamic theory of knowledge governance is proposed based on the tentative application of this unified theoretical framework in the case of upstream petroleum industry.

The dominance of a *specialized growth innovation strategy* by most of the agents in the *dis-integration* period is explained by relative low transaction costs stemming from dominance of the breadth type of complexity. The emergence of Integrated Service Companies as leading actors with aggressive *diversified growth innovation strategies* in the *neo-integration* period is interpreted as a sector-wide response to the emergent systemic complexity. It is explained that systemic complexity involves high transaction costs in knowledge generation processes and requires new system integration capabilities. In fact integrated service companies are understood as new agents in the sectoral innovation systems of upstream petroleum industry which are gradually created to serve a new function. This new function, the governance of excessive systemic complexity, emerged in the most recent period.

The *dis-integration* period seems consistent with the *vanishing hand* (Langlois, 2003) idea where reliance on external knowledge sources increases and companies tend to specialize and outsource their non-core knowledge activities. However *neo-integration* period suggests that an *emerging hand* of corporate management can become critical when systemic complexity prevails. New/latecomers - be they organisations or nations - find it difficult to learn/absorb the set of integrated knowledge required to do a proper job and be competitive. Since this has been accumulated over several decades by incumbents, latecomers struggle to catch up with leaders.

In addition to the methodological and empirical contributions involved in the examination of the two hypotheses regarding the governance of complexity, an important theoretical implication is drawn. It is argued that integration of dynamic and three-dimensional perceptive of knowledge base complexity can extend two existing research traditions, providing two complementary theories of the dynamics of knowledge governance. One is rooted in the *Schumpeterian* tradition, while the other takes a *functional* approach based on transaction-cost economics and resource-based theories of the firm. These theoretical contributions deepen our understanding of the drivers of change in systems of knowledge governance as a sector-wide response to shifts in knowledge base complexity. This also facilitates integration of both traditions. It is possible, on this basis, to analyse the role of geography in coping with the dynamics of complexity and how knowledge is integrated and coordinated across geographical distances. This paves the way to understand the role of knowledge base complexity in technological catch-up of latecomer countries, and how the dynamics of geographical pattern of innovation is affected by the dynamics of knowledge base complexity.

8.3.3. Geographical implications of evolving knowledge base complexity

In order to answer the third research question which addresses the geographical implications of the knowledge base complexity, the following hypothesis is proposed:

Hypothesis 4: 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.*

In other words, systemic complexity seems to favour incumbents (be they firms or countries) at the expenses of new/latecomers. We examined whether this occurrence is reflected in the dynamics of geography of innovation patterns?

We found empirical evidence in the upstream petroleum industry in support of the hypothesis. It is shown that the increasing breadth complexity in p1 provides wider opportunities for catch-up of other countries and more rapid geographical dispersion. In contrast, increasing systemic complexity slows down geographical dispersion. It seems this condition is more in favour of bigger innovator countries and companies that originate there.

However the analysis also shows that those wider possibilities in the conditions of dominance of breadth complexity are not open equally to everybody. The co-existence of local sectoral production experience as a demand side of innovation and supportive national systems of innovation in the supply side are preconditions to both realize these innovation opportunities and exploit them at global level. Without these preconditions, it is very unlikely for companies of latecomer countries in the sector to overcome the cognitive barriers which inhibit many oil producing countries from gaining higher positions in the technological hierarchy of petroleum industry.

Consequently, only a few latecomer advanced countries (UK, Norway, and Canada) are recognized as important catch-up nations, while a few other less developed countries (Brazil, China, Saudi Arabia, etc.) have changed marginally. In addition, the results suggest the idea that in dealing with systemic complexity, cognitive and organizational proximity achievable through the internal networks of big multinational companies might be more important than geographical proximity.

The empirical evidence of geographical patterns of innovation offer conceptual clarifications and valuable theoretical insights. We observed that systemic complexity implies higher geographical proximity, because coordination and integration of different segments of knowledge is challenging over long distances when there are intensive interactions. However, if the complexity is more of the breadth and depth type, when 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 can be associated with different geographical impacts. Some of the ambiguities and inconsistencies in the literature come from lack of clear distinction between these dimensions and their various impacts.

In addition, the empirical results offer some theoretical insights concerning the dynamics of geographical patterns of innovation. We found that the standard internationalization theory of innovation is not sufficient to explain *three* aspects of geographical dynamics. These are: temporal mismatch between international geography of oil production and innovation; slowing down and eventually stop in geographical dispersion in later periods of upstream petroleum industry; and, divergence of geographical dispersion trends when measured based on inventors and assignee' countries. These three aspects in the dynamics of geographical patterns of innovation are better understood in the light of the dynamic and three-dimensional concept of knowledge base complexity. We also found that the observed dynamics in the international geography of innovation progress in accordance with the dynamics of knowledge base complexity over time. The knowledge base of the industry goes from a state of relative simplicity to the dominance of breadth and then systemic complexity. In parallel, the geographical dynamics of innovation advance from relative non-internationalization, to internationalization, and finally to globalization. The findings offer valuable insights for development of a dynamic theory of geography of knowledge base complexity, as an attractive area for further research.

In sum, the dynamic and three-dimensional perspective to knowledge base complexity offers three theoretical implications. First, understating the industry lifecycle with reference to the structure of the knowledge base. Second, provision of a dynamic theory of governance of knowledge base complexity within two complementary frames of Schumpeterian and functional approaches. Third, explaining the dynamics of geographical patterns of innovation and catch-up processes. These results also have some policy implications explained in the next section.

8.4. Implications for policy

The empirical analysis presented above suggests that the upstream petroleum industry involves both considerable opportunities and significant challenges for economic development in resource based countries. The role of policy is therefore defined in support of economic agents to overcome the challenges and exploit the opportunities and transform the danger of resource curse to the fruits of a blessing. No industrial policy can be successful without deep understanding of the nature of the evolution of the industry and its underlying knowledge processes. The insights presented in this thesis with regard to evolving knowledge base complexity and their implications for patterns of innovation at sectoral, organizational and geographical level can inform industrial policy in several ways.

First, the evidence presented clearly illustrates widespread and increasing innovation opportunities in upstream petroleum industry which justify policy interventions targeting knowledge-centred development agenda. According to the new industrial policy approach (Rodrik, 2007, 2008; Hausmann and Rodrik, 2006), technological dynamism and potential knowledge spillovers are crucial for an industry to be the subject of policy interventions. In contrast to what is normally portrayed by the resource curse thesis, the upstream petroleum industry illustrates a pattern of growing innovation opportunities, a broad scientific and technological base, and wide inter-sectoral interaction with other industries. Other secondary evidence also shows that the sector can be a source of skill-intensive job creation and knowledge based growth, if its wide network of supplier base and input industries are taken into account (Sæthe et al., 2011; Oil and Gas UK, 2011).

Underestimation of learning opportunities in the upstream petroleum industry is a wrong conclusion, often implicitly drawn from a conjecture that industries matter in their developmental opportunities. Although the general statement which has been subject of an old debate (from Prebisch, 1950; Kaldor, 1981; Reinert, 1998; to Hausmann and Rodrick, 2006) is acceptable, the immediate conclusion that all resource-based industries are of low opportunity category is not acceptable. Today’s situation within the petroleum industry clearly falsifies this assumption, even if it has been the case years ago.

Accordingly, the role of policy is to create an environment in which these innovation opportunities are realized and exploited properly in resource producing countries. It is far more important to analyse ‘how’ these countries produce their natural resources than ‘what’ they produce (Lorentzen, 2008a). The role of industrial and innovation policy is to contribute to the shaping of this ‘how’. As explained in section 8.3, the necessary conditions for productivity growth, formation of forward and backward linkages and innovative capacities are technological learning and accumulation of capabilities. Without these capabilities, the economic agents are unable first to realize the high potential innovation opportunities involved in resource based industries, and second, take entrepreneurial action in order to transform these opportunities into profitable economic activities. In other words, “learning how to seize technological and organizational opportunities is a fundamental driver of industrialization” (Cimoli et al., 2009a, p. 10).

The metaphor of ‘fishing in the sea’ is illustrative (Dosi et al., 2006). Innovation opportunities refer to the fishing potential of the sea determined by the size (depth and width) and richness of the sea. However, ‘the rate of fishing’ from the sea by different fishermen depends on their skills and capabilities. If inexperienced fishermen are unable to catch high volumes of fish and make profits out of them, we cannot blame the sea for its low fishing potential (or blame the sector for its low innovation potential). The solution is to support learning processes and increase the capabilities which allow firms to realize and exploit opportunities.

However, learning, knowledge accumulation and formation of capabilities are not automatic self-sustained processes particularly in the latecomer context. This is why public policy should play a role. As previous research has argued (Bell, 2007; Rodrik, 2007), these activities are subject to large technological, information and coordination externalities. As a result, the standard argument applies - that investments in creating knowledge assets and learning processes will be considerably less than what is socially efficient and desirable. This is because if they are initiated by some economic agents, other enterprises can get access to the knowledge generated, information produced, and benefit from infrastructure and linkages created, without compensation to the original investor. Consequently, there is an important role for the government to support these activities by different means.

In this view, ‘industrial policies are a predicament’ and governments are ‘doomed to choose’ (Hausmann and Rodrick, 2006). This is because countries inevitably have the choice to shape the future paths of knowledge accumulation and capability building. “Even the choice of not having any (implicit or explicit) industrial policy is a choice in itself, that is, the acceptance of the current international division of intellectual and physical labor, and with that the current distribution of learning opportunities” (Cimoli et al., 2009a, p. 2). However, this choice is not a sustainable and reliable development path, because the general economic environment in less developed countries is often not conductive to learning processes, depriving them from benefits of emerging innovation opportunities.

Second, the evolution of the knowledge base complexity in the upstream petroleum industry offers another and perhaps more important implication for policy. Although accumulation of learning capabilities is a key to embrace innovation, what needs to be learnt is not a ‘fixed’ target on the shelf. If it were, most of the countries soon or later will have achieved the goal, whatever their efforts and speed of learning. On top of learning obstacles explained above, the evolving knowledge base complexity of the sector plays the role of a moving target for latecomers, which increases the entry barrier to the innovators’ club. The more complex is the knowledge, the more challenging are the processes of learning and diffusion to the latecomers. The increasing nature of knowledge cumulativeness arsing from complexity could be an important factor, preventing technological convergence between different countries starting at different technological levels (Dosi, 1982).

Even when the rising complexity is of the breadth type, the window of opportunities is open only for those who are able to recognize these opportunities. Without prior absorptive capacity (Cohen and Levinthal, 1989) and technological capabilities in particular specialized fields, economic agents cannot make sense of emerging opportunities and exploit them. When the complexity turns to the systemic type, which implies simultaneous specialization, in increasing different range of fields and the ability to integrate and combine them, the learning challenges for latecomers are much greater. This is because the specialized knowledge on its own loses its advantage and is only valuable if other pieces of complementary knowledge are available or accessible, and also with the knowledge to combine and recombine them in the system. This is why system integrators in upstream petroleum industry play an increasing role in the knowledge production processes. They not only develop specialized knowledge internally and know where the knowledge can be found externally, their core capability is the ability to coordinate and integrate these distributed pieces of knowledge. These system integration capabilities allow monitoring and shaping of the future trajectory of innovations, coordinating technical change in the supply chain and designing new system architectures (Granstrand, et al., 1997).

Learning increasingly complex knowledge is subject to higher coordination costs, longer time periods, and perhaps wider externalities. In addition, it involves great levels of absorptive capacity and investment in research and development. This is why it is very unlikely that private companies will invest in the development of capabilities in complex industries. The aircraft industry as an example of complex sectors is an illustrative case. It is far from reality to believe that Boeing in the US and Airbus in Europe could have been developed without strong government support, not only in technological learning and R&D investments, but also by securing the market (Niosi and Zhegu, 2008).

The challenge of technological catch-up in such complex industries for latecomers is even higher, as their companies are not supported by an advanced national innovation system. Irrespective of the opportunities available in the international knowledge frontier of many industries (such as aircraft or petroleum), the lack or gap in capabilities is a key obstacle for entrepreneurial exploration of these opportunities and exploitation of their economic benefits (Cimoli et al., 2009a). When industries like aircraft or upstream petroleum are systematically complex, filling the gap is more challenging and costly, because of the existence of a strong collective element. Complex industries are metaphorically like the far deep sea with plenty of fish. Although the challenge is not shortage of fish, fishing in this sea is different from fishing in easily accessible seas. Complementary assets (Teece, 1986) and capabilities like advanced ships, equipped with monitoring instruments, are required to explore where fish are deep at the bottom of ocean and then to catch them.

The required capabilities do not consist of a small set of specialized knowledge to be learnt, but also an increasingly wide range of related technological areas. In addition system integration capabilities are the key to technological catch-up in complex industries in the latecomer context. The concept of latecomer system integration capability (LSIC) has recently been introduced to explain the role of system integrators in the catch-up of latecomer countries in complex products and systems (CoPS) industries (Kiamehr, 2012). That analysis highlights the key role of coordination and integration of parallel and distributed learning processes in multiple actors in the supply chain of the sector, in the process of technological catch-up in complex industries. What made this happen in Iran’s power plant industry, in this case (Kiamehr, 2012), has been strong government commitment to support learning and capability building processes through a variety of means. This includes preferential access to the local market, investment in skills development, acceptance of a scope of risk in the early stages of development – such as time and performance deviations, and encouragement for local sourcing.

The experience of technological catch-up in petroleum industry in Norway and Brazil provides similar evidence. We observe the key role of latecomer systems integrators (Statoil and Petrobras) in support and coordination of learning processes in a wide network of supplier and partner companies, along with developing systems integration capabilities for themselves (Sæthe et al., 2011; Engen, 2009; Dantas and Bell, 2009, 2011). No individual company would have been willing to follow these parallel networked learning processes, without strong government support. In fact both Statoil and Petrobras were state-owned companies with national interests at the time of catch-up processes, although they were partly privatized later on. As a result, in addition to business oriented goals, they also were a policy tool to meet the national interests of their country.

In sum, systemic knowledge base complexity calls for an ‘additional’ role to be played by government in support of catch-up processes in complex industries, if innovation opportunities are to be seized in latecomer countries. This is ‘additional’, because technological learning and capability building processes are not generally encouraged by market based mechanism even in non-complex sectors at basic levels, let alone in complex industries. The experiences reviewed show that such extra roles which involve integration and coordination of distributed learning, are often served through state-owned latecomer systems integrators as a policy tool for catch-up in complex industries. However there might be other instittutial arrangements doing similar jobs in other contexts. As Breschi and Malerba (2000) explain, both vertically integrated structures and geographically co-located dis-integrated structures may provide suitable coordination. For example, in advanced industrial countries where general innovation infrastructure is established, networked firms may govern innovation processes well. However, in a latecomer context where many knowledge inputs and infrastructure are missing, big integrated companies seem more efficient to compensate for institutional weaknesses.

The evidence suggests that firms operating in complex industries in the latecomer context can face a vicious cycle preventing them from learning and building technological capabilities. This is because clients are often conservative in giving the complex project to the local systems integrators that are less experienced compared to international competitors. Local systems integrators are also reluctant to source their key components from local suppliers which are may be less competitive compared to their international counterparts. This tendency keeps the links of the value chain weak in the local market and prevents user-producer interactions (Lundvall, 2009) and accumulation of knowledge and capabilities over time. Limited learning feeds back to the capacity of local firms to explore and take advantage of innovation opportunities, creating a vicious circle. Governments can help to break this cycle, either as the main client at the top end of the value chain, or as state-owned systems integrators one step back. This can be done through public procurements programmes in which the initial risks and lower performance of local suppliers are tolerated (Kiamehr, 2012).

What seems common in all successful industrial policies is that they employ different kinds of tools and schemes to create an incentive structure favourable for “learning-based” rent-seeking. To be effective however, they should also curb what has been called “rent-seeking tout court”. Management of balanced rent distribution with respect to both elements is one of the most difficult and challenging parts of any technological catch-up strategy (Cimoli, 2009b). This task is even more difficult in resources based countries, given the easy availability of natural resource rents which tend to distort balance in the cost of the former and in favour of the latter. It is up to the governments of these countries to choose the balance and get a better position in international distribution of learning capabilities.

8.5. Limitations and suggestions for further research

This research was an attempt to explore the dynamics of knowledge base complexity and its relationship with patterns of innovation at sectoral, organizational and international geographical levels. The findings have some limitations with respect to the conceptualization, the empirical setting, the data sources used, and the methodology employed. Each of these limitations could be seen as an opportunity for the extension of this research.

With respect to conceptualization, I limited the scope of the analysis to the role of knowledge base complexity, from among other elements of technological regimes and characteristics of the knowledge base. As sectoral innovation systems approach broadly suggests, the dynamics of other elements of technological regimes such as the degree of tacitness, appropriability, etc. can also have impacts on the patterns of innovation at different analytical levels. In particular, it would be interesting to explore which characteristics in general facilitate knowledge diffusion and learning, and which of them hinder it. The broad lesson of this research is that the nature of knowledge base, as a collective and distributed system, matters for catch-up processes. Deep understanding of these characteristics could help to develop more effective strategies for latecomer firms to catch up with leaders, and strategies for governments aiming to speed up industrialization and catch-up processes.

One other venue for the theoretical extension of this line of research is the development of theoretical formal models such as history-friendly (Malerba et al., 1999; Malerba et al., 2001, Malerba and Orsenigo, 2002; Malerba et al., 2008) or agent-based models (Pyka and Fagiolo, 2005) in order to explain the role of knowledge characteristics in catch-up processes. With particular focus on the role of complexity in petroleum industry, this research provides rich data and broad historical trends, in addition to the conceptual base required for these kinds of modelling.

The challenges of technological catch-up in the petroleum industry were analyzed in terms of a knowledge governance framework where accumulated complexity increases the entry barriers for latecomers. However, alternative readings may also be possible within other analytical frames.

Technological catch-up could be analyzed in a political economy framework. This sector exemplifies an industry with high level of government intervention both at national and international levels. The critical role that the petroleum industry plays in the global economy implies financial, economic, technological and even social imperatives. These broad forces could be analyzed within a political economy framework exploring their role in shaping technological competences of different countries. For example, oil supply security has been an important driver towards investment in technological capabilities in this sector in many countries, such as France in the past and China more recently, On the other hand, one may argue that world powers use their technological dominance to reinforce the current political order against many oil producing countries. This acts to control oil markets and prevent instability in the global economy.

A different, but complementary perspective is to put firm business strategy and its role in formation of technological capabilities at the centre of the analysis. In many oil producing countries, national oil companies are the biggest source of government revenue. Increasing levels of production is often a much higher priority than increasing local technological capabilities. The source of production technology is often advanced international companies and national oil companies are only the users. Only when required technologies cannot be accessed from international markets, is there a strong driver to build internal capabilities. This happened for Petrobras when deep offshore technologies had not been developed while it expanded offshore production. The Iranian oil company is now initiating several technological programs, as they can no longer be sourced from foreign sources, due to imposed sanctions.

In terms of its empirical setting, the findings of this research are based on the study of innovation processes in the upstream petroleum industry at the aggregated level. Surely, there are some particular technological areas within upstream petroleum industry which do not follow the general argument. For example, the diffusion of ICT in some parts of the industry has facilitated knowledge codification, modularization and decomposition in some segments. This means that reduced systemic complexity has enabled the emergence of some specialized companies in other countries, for example in the data interpretation business, as a knowledge intensive segment in the value chain. However, this does not mean that the overall skewed distribution of learning and innovation capabilities have become more balanced among leading and latecomer countries. Accordingly, one attractive research area would be to explore some examples of successful technological catch-up in particular knowledge intensive segments of the upstream value chain by latecomer countries and the factors which enabled this to happen. Concrete understanding of these examples could contribute to the development of catch-up theories in the context of complex industries, which are not generally catch-up friendly.

Also, we should be cautious about generalizing the findings, to other segments of the petroleum industry in mid or downstream, to other industries in general and to other resource based industries in particular. Crude empirical inter-sectoral generalizations could be misleading at best and harmful at worst, as the history of resource based theories in section 8.2 teaches us. It is misleading because it could provide an unrealistic picture of the developmental or anti-developmental capacities of unexamined industries. It is harmful, because endowed countries may lose their developmental opportunities next door, and look for them in inaccessible remote areas[26]. It is more realistic for resource based countries to build technological capabilities around natural resource industries using years of accumulated production experience. It is normally unrealistic to expect the formation of unrelated high-tech sectors without prior industrial experience, like a cathedral in a dessert.

However, it is also true that these countries should be careful about industrial lock-in and follow smart but realistic diversification strategies. What is badly needed is deep investigation of innovation opportunities and the level of complexity in other

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[26] There is a Persian poet saying: “The partner is at home, yet you are looking around the world; the water is in the jug, yet you are moving thirstily around”

industries, particularly other understudied natural resource based industries. This is an unexplored research area just emerging, looking at natural resource based industries from the learning and innovation perspective. Any new research in this direction is likely to create both theoretical contributions and policy relevant implications. For instance, it would be very interesting to see whether the full cycle of dis-integration and neo-integration observed in the upstream petroleum industry can be observed in other sectors. Is it a unique and sector-specific phenomenon or a more general pattern that can be observed in other sectors of the economy? In particular, the validity of the *emerging hand vs. vanishing hand* idea in other industries and its association with dynamics of knowledge complexity is an open question for future research.

The potential role of policy in fixing the challenges of catch-up, particularly when systemic complexity is high and there are widespread inter-dependencies, is another critical line of enquiry. We need to know much more about how innovation and catch-up policies should be designed and implemented in these conditions. One important question is: what kind of institutional structures can support and facilitate long-term learning processes in complex industries for latecomer countries? We should move beyond the question of 'why industrial policy?' and try to answer ‘how’ an effective industrial policy should be designed and implemented (Rodrik, 2008). What are the main characteristics of institutional design (Rodrik, 2007) for successful catch-up in complex industries? Comparative analysis of both successful and unsuccessful industrial and innovation policies in complex industries could shed light on the main requirements of catch-up in latecomer contexts.

The main data source for the current study was patent data, with its well-known limitations in representation of technological knowledge and innovation (chapter 2, section 2.5). With regard to this research, three limitations are important. First, the patent data in upstream petroleum industry tend to underestimate the level of innovativeness, because patents are not the major method of innovation protection, particularly in small and medium firms which can’t afford its costs. Nonetheless, this limitation creates over-confidence in the claims about innovativeness of the industry. Second, the measures of systemic complexity based on co-classifications also tend to underestimate the linkages and interactions between different innovations. This is because some types of inter-relationships are not necessarily captured by patent co-classifications. For example, many potential linkages and possible recombination opportunities are explored by companies and innovators long after patents are granted. Such linkages have not been visible to be captured by patent examiners at the time of the original innovation.

Third, patents also may considerably underestimate the level of technological catch-up by less developed latecomer countries. There are many difficult stages and a long path before companies in the latecomer context achieve the international knowledge frontier which creates patentable innovations. The implication is that some of those countries which have low positions in innovation rankings, and do not show catch-up patterns based on patent data, may have achieved certain levels of technological progress, below patentable innovations. As a result the complexity argument is directly valid for this world frontier level of knowledge production.

Nonetheless, it is in principle extendable to lower levels of technological capabilities, as far as we look at patents as traces of knowledge (as explained in chapter 5), not just novel inventions. In other words, if the range of technological fields and their interactions are increasing over time, as reflected in patent data, a similar pattern would also be expected at lower levels of technological capabilities, for example at more imitative operational and production levels.

What makes me relatively confident is that almost all the results here are drawn from trend analysis, rather than actual levels. Therefore, I expect that the three above mentioned limitations of the patent data and other under/over estimations have not considerably affected the conclusions. In other words, if the data is corrected for the under/over estimations, the trends should largely remain the same, even if the levels of the variables are affected. In addition, in-depth qualitative case studies are a complementary research strategy which can be employed in future research to triangulate the findings. I would personally recommend a qualitative case study about the factors driving the emergence of major big integrated service companies to recheck the validity of emerging arguments around coordination of increasingly complex knowledge.

With regard to the quantitative methodology, the proxies I used in this research may have their own limitations in capturing what they meant to capture. This is a general challenge of many quantitative studies in general, and patent statistics in particular. Noise and abrupt changes in the data are relatively high which sometimes makes interpretation difficult. While I tried to use best known techniques to develop reliable proxies and minimize noise, there is still a big opportunity to improve the quality of the proxies. For example, it is very important to scrutinize the analysis of dynamics of complexity in the three dimensions in future research, because this was the most novel aspect of the quantitative analysis carried out in this research. Limited availability of prior research on this topic was an important constraint for development of proxies and their interpretation.

Development of this strand of research by examination of new proxies and use of other data sources is highly recommended. For example, in order to assess systemic complexity, other proxies can be designed and tested to capture different aspects of systemic complexity like coherence (Krafft et al., 2009) or decomposability of the knowledge base(Yayavaram and Ahuja, 2008). Social network analysis is another analytical tool which could be helpful to understand the dynamics of the structure of the knowledge base (Kraft et al., 2011). The information embodied in patent citations (Jaffe and Trajtenberg, 2002; Brusoni et al., 2005 could be used to correct for the quality of inventions. Since they also reveal the knowledge flows and the vertical links between patents (Jaffe and Trajtenberg, 1999), they could potentially be used to develop new proxies for systemic complexity. Another application is to analyse the role of international knowledge flows in catch-up processes in order to develop catch-up theories.

There is large room for conceptual and theoretical, methodological and empirical extensions of the current research. Each offers an attractive area for future investigation.

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Appendix I: Derwent Classification Codes: Section H (Petroleum)[27]

Comprehensive coverage of all aspects of the oil and gas industry with limited coverage of competitive products e.g. coal and peat.

Table A-1 Derwent Classification Codes: Section H (Petroleum)

Derwent Class Codes are listed in the first column of the table below. Approximate IPC codes are given in parentheses.

H01	Obtaining crude oil and natural gas - including exploration, drilling, well completion, production and treatment. General off-shore platform and drilling technology is included together with the treatment of tar sands and oil shales (C10G, E21B).
H02	Unit operations - including distillation, sorption and solvent extraction (C10G).
H03	Transportation and storage - only large scale systems are included. Road tankers and retail petrol station-type applications are excluded. Treatment of pollution from marine oil tankers is included.
H04	Petroleum processing - including treating, cracking, reforming, gasoline preparation - biosynthesis based on hydrocarbon feedstocks is included (C10G).
H05	Refinery engineering.
H06	Gaseous and liquid fuels - including pollution control. Chemical aspects of catalytic exhaust systems for cars are included as well as liquid or gaseous fuels of non-petroleum origin eg methanol or ethanol-based fuels. Combustion improvement additives for liquid fuels are included (C10L).
H07	Lubricants and lubrication - this excludes self-lubricating surfaces eg PTFE coated surfaces and lubrication systems in general. The section includes lubricants of non-petroleum origin eg silicone oils (C10M).
H08	Petroleum products, other than fuels and lubricants - this includes hydraulic fluids and electrical oils even when of non-petroleum origin (C10M).
H09	Fuel products not of petroleum origin - excluding coal handling, preparation or mining, but including coking, briquetting, peat processing synthesis, gas production, coal gasification. Combustion improvement additives for coal, peat and other non-hydrocarbon based fuels are included in this Section together with coal liquefaction and desulphurisation.

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[27] http://science.thomsonreuters.com/support/patents/dwpiref/reftools/classification/dclassh.html

Appendix II: Derwent Manual Codes for upstream petroleum industry (sub-section H01)

Table A-2 Derwent Manual Codes for upstream petroleum industry (sub-section H01)

H: PETROLEUM

Code commenced at CPI Week 197001.

H01 CRUDE OIL AND NATURAL GAS

Code	Description	Year
H01-A	EXPLORATION	
H01-A01	**Geological; geophysical** E.g. seismic exploration	
H01-A01A	. **Seismic surveying** For exploration prior to well drilling. For well logging see H01-A02	2006
H01-A02	**Well logging, general**	
H01-A02A	. **Electric logging**	1986
H01-A02B	. **Radioactive logging**	1986
H01-A02C	. **Acoustic logging**	1986
H01-A	Unclassified	197031
H01-B	DRILLING	
H01-B01	**Marine structures and equipment**	
H01-B01A	. **Fixed multi-well platforms**	1986
H01-B01B	. **Mobile jack-up platforms**	1986
H01-B01C	. **Drill ships**	1986
H01-B01D	. Semi-submersible platforms	1986
H01-B01E	. Decommissioning of marine production platforms Including reuse of upper parts, such as decks	2002
H01-B02	Slim hole drilling	
H01-B03	**Rotary drilling**	
H01-B03A	. **Derricks, rig floor equipment** Including downhole blowout preventers	197031
H01-B03A1	.. Derricks	1986
H01-B03A2	.. Drilling mud mixing and return mud processing	1986
H01-B03A3	.. **Hoisting and rotating equipment**	1986
H01-B03B	. **Well control equipment.** Also includes logging-while-drilling and measuring and controlling downhole conditions/parameters, etc.	197031
H01-B03B1	.. **Logging while drilling**	1986
H01-B03B2	.. **Measuring procedures and equipment**	1986
H01-B03B3	.. **Valves and control equipment** Including downhole blowout preventers	1986
H01-B03C	. Subsurface equipment	197031
H01-B03C1	.. **Drill bits**	1986
H01-B03C2	.. **Drill collars**	1986
H01-B03C3	.. Drill pipe	1986
H01-B03C4	.. Kelly	1986
H01-B03C5	.. **Drill and casing protectors, Centralisers**	2006
H01-B03C6	.. **Drilling riser**	2007
H01-B03D	. **Transmission/generation of power, data etc.** Includes cables, connectors, antennae etc. for downhole use	2005
H01-B04	Cable drilling	
H01-B05	**Other drilling methods and equipment** Including electric, explosive, thermal and hydraulic, also includes under-reamer assemblies	
H01-B05A	. **Directional and turbo-drilling**	1986
H01-B05B	. **Coring** E.g. sampling	1986
H01-B06	**Drilling fluids**	1994
H01-B06A	. **Water-based drilling fluids**	1986
H01-B06B	. **Oil based drilling fluids**	1986
H01-B06C	. **Drilling fluid additives**	1994
H01-B07	Fishing and retrieval tools	
H01-B08	**Testing operations and equipment, general**	1986
H01-B	**Unclassified**	

H01-C	WELL COMPLETION, STIMULATING, AND SERVICING	
H01-C01	Casing and tubing excluding well packers, general	
H01-C01A	. Well packers	1986
H01-C01B	. Joining of casing Includes of formation of joints and lateral wellbore sections	2005
H01-C02	Cementing	
H01-C02A	. Methods and equipment	1986
H01-C02B	. Cement compositions	1986
H01-C03	Fracturing	
H01-C04	Acidising	
H01-C05	Perforating	
H01-C06	Wellhead equipment, general	
H01-C06A	. Blowout preventers	1986
H01-C07	Screens and liners	
H01-C08	Gravel packing	
H01-C09	Consolidation of incompetent formations	197031
H01-C10	Servicing E.g. cleaning deposits	197031
H01-C11	Testing, control operations and equipment, general	1986
H01-C12	Water control compositions For methods, see H01-D14	2005
H01-C	Unclassified	197031

H01-D	PRODUCING	
H01-D01	Oil-lifting equipment	
H01-D02	Gas-lifting equipment	
H01-D03	Pumps	
H01-D04	Separators	
H01-D05	Marine production equipment	
H01-D06	Waterflooding.general	
H01-D06A	. Brine flooding	1986
H01-D06B	. Steam flooding	1986
H01-D06C	. CO2 flooding	1994
H01-D06D	. Polymer flooding	2002
H01-D06E	. Alkaline flooding	2002
H01-D07	Repressuring	
H01-D08	Thermal methods E.g. steam injection, microwaves, etc.	
H01-D09	Chemical methods	
H01-D10	Oil shale treatment and equipment	
H01-D11	Tar sands treatment and equipment E.g. bitumen extraction	
H01-D12	Testing, control operations and equipment, general	1986
H01-D13	Methods using bacteria	1994
H01-D14	Water control methods For compositions, see H01-C12	2005
H01-D	Unclassified	

H01-E	TREATING AND TESTING Does not include well treatment procedures already covered in H01-C:	
H01-E01	Emulsion breaking, desalting and dehydrating	
H01-E02	Corrosion inhibiting	
H01-E03	Testing crude oils	2005
H01-E04	Water Treatment Includes composition e.g. anti-sludging agent, and apparatus	2010
H01-E05	Scale Inhibition	2010
H01-E	Unclassified	

H01-F	NATURAL GAS	
H01-F01	Field treatment and processing	197031
H01-F02	Liquefaction methods and equipment	197031
H01-F	Unclassified	197031

H01-G	EXTINGUISHING OIL WELL FIRES	1994
H01-G01	Explosives	1994
H01-G02	Capping	1994
H01-G	General	1994

H01-H	**WELL KILLING**	**2010**
H01-H	**General**	**2010**
H01-P	**OIL AND GAS WELL PIPES** Includes pipes used during well drilling, completion and production	**2010**
H01-P	**General**	**2010**
H01-R	**DEPLETED OIL/GAS FIELDS**	**2010**
H01-R	**General**	**2010**
H01-X	**OTHER**	**2010**
H01-X	**General** Includes well tractors and protective clothining	**2010**

Appendix III: Imperfections in geographical patent information

In order to implement the geographical part of the analysis (answer to the third question of the research reported in chapter 7), we need to know the size of the contribution of each country in technological innovation and its change over time. As explained in the chapter 2, the number of international families invented within each country could be a reliable and comparable measure based on which we could trace the changing relative position of the countries. In other words, when the aim is to trace the inventive performance of the countries, residence country of inventor is the most suitable reference country to be attributed to the patent (OECD, 2009). It is important to note that, part of these inventions within a particular country might be owned by foreign and international companies. These are those innovations usually performed in R&D facilities of international companies in the countries other than their home country.

One criticism might be that this measure overestimates the real role of host countries, because it attributes the innovations of foreign companies to their host countries. However, this innovative performance could be more the result of technological capabilities in the home country of international companies. Although this argument seems acceptable, it does not contradict the fact that increase in the innovative performance of international players within a particular country could be an 'indirect' measure of innovative performance of that country. The decision of international players to establish innovation centres in other countries could have a strong relationship with R&D facilities, innovation infrastructure, professionals and knowledge externalities which is available in that country. Overestimation also would not seem serious problem as soon as our main concern is change of shares over time, not the absolute measures. Overall, there is a common agreement within patent statisticians that the best reference to measure inventive performance of countries is inventor's country of residence (OECD, 2009).

One alternative that might seem better at first glance is using applicants' country rather than inventor country of residence. The argument in favour of this option is that ownership of innovation is more important regardless of where it is produced. In other words, it is more relevant to know who controls the production and application of innovations, not the location where they are innovated, particularly when the aim is to understand the position of different countries in a sectoral innovation system.

Although reasonable, there are some important methodological challenges which downgrade the use of applicants' country to compare innovative performance of different countries. First, given the major share of international and multinational companies in innovation processes, there is no reliable method to attribute their innovation to different companies. In fact, it is very difficult to assign these major players to any particular countries. Suppose Schlumberger Company with operations, affiliates and R&D facilities in a large number of countries. Originally, it was an

American and French company but is now a highly multinational company. Should innovations by this company be assigned to US or France as the country of origin? Should we assign the innovations to the country of the affiliate or the branch within which innovation happened? This is similar to 'country of inventor' issue discussed earlier. The relevant choice highly depends to the purpose of the study.

The second important issue to work with the data of applicants' country is noise in the data. In fact, for some important companies, registered applicants' country is not either home country or inventor country. It is simply the country of those affiliates who are experts in the legal protection of innovations. This could be different from both headquarter country or invention country. Other factors such as regulations and financial considerations could distort the applicants' country data from reflecting innovative performance of the countries. Virgin Islands (British), Panama, Netherlands Antilles are the countries whose ranking appears strange in table 7.1, because they appear higher than many important countries in the industry.

Simple analysis of patent applicants in these countries shows that major multinationals have decided to report from these small countries, as their registered country, rather than their main county of origin for legal or tax related reasons. Given this noise in the applicants' country data, the inventor's country of residence seems the best choice. The country of inventor is the relevant field in the person's table of PATSTAT database which assigns a patent application to one or several inventors. They are characterized by a standard code, name, and the address including the country of residence.

Unfortunately, this table in our dataset has many missing values where the inventor record of a patent application is not available, or its country of origin is not reported. Overall, 266675 application-inventor combinations, which is about the 52 percent of total observations, are complete in their country field. Nonetheless, there are some possible alternative ways in which missing data could be completed with acceptable estimations. I introduce these alternatives, estimate the margin of error that might produce, and explain the number of records is filled using these strategies.

Because our analysis is based on international patent families, not applications, and for each family there are several correspondent applications, each of which could display the inventor country of the family. Therefore, among 115104 total numbers of families within our dataset, 56944 (%49) families have reported inventor country from PATSTAT persons table.

There are three potential sources by which we are able to complete the country field of other applications or patent families, and guess their country of invention with certain level of reliability. The first source is the priority country in which the patent application is first registered. The second source is the assignee countries where patent applicants come from. Third is the main invention country of patent applicants which means attribution of patents to a country in which patent applicants perform a majority of their inventive activities. To explore the degree of confidence of these three sources, I evaluate error margins, in the observations we already know the country of inventions. In other words, I measure the degree of error in using the above mentioned sources to complete the data set, assuming more or less similar level of error is expected in the unknown subset. Then, I use the most reliable methods to complete the dataset. Sometimes these methods are used in combination to increase accuracy and decrease the possibility of error, as be seen below.

1- Priority country as the source[28]

To evaluate the reliability of employing priority country as invention country, I measure the percentage of patent families with known inventors in which priority country is the same as that of inventors. To have tougher measure and reduce the error, I also calculate the same measure but for those families with the same priority and assignee country. Among 56925 patent families with known inventors, 52224 families have same inventor and priority country which means about 92 percent accuracy.

To increase the accuracy of estimation and reduce the error, I decided to apply a more tight criteria, using priority country as the inventor country where it is the same as the assignee country of the patent family. In fact this is the combination of first two sources of priority and assignee country to increase the reliability. The reason is that companies tend to first apply for a patent in their home country. Among 48770 patent families which their inventors, assignees and priority country are known and priority and assignee countries are the same, 47889 have the same inventor country. This means that in more than 98 percent of families we could replace priority country as inventor country if it is the same as assignee country. This high degree of reliability does make sense because, it is highly unlikely for a company to do invention in one country, but first seek patent for this invention in other countries (priority country) where it is also different from assignee country.

2- Assignee countries as the source

To evaluate the reliability of using assignee countries of applications as their invention country, I selected all patent applications in our dataset with known assignee countries.

Then I followed two different methods of estimations. In the first method, I have calculated the percentage of these application-assignee combinations in which inventor country of the application is the same as its applicant. This method measures the degree of error at invention level when all applications aggregated. This provides us an aggregate degree of confidence when using the assignee country

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[28] The priority country has been used in a recent study as the country of invention in ICT industry (see Antonelli, et al. 2010 p.57 for more information)

instead of inventor country. It calculates what percentages of inventions, assignee countries and inventor countries are the same. Employing this method, 102,835 out of 106867 applications had the same country and 4,032 had different countries. This means that this method has 96 percent of accuracy. Nonetheless, this percentage may not be uniformly distributed among assignees, because some assignees may just do their inventive activities in their home countries. Others, particularly international companies may do inventive activities in several countries but assign those activities just to their headquarters or important affiliates. Since application of this method tends to underestimate latecomer countries, it will not produce serious problem for our analysis when the aim is to analyze catch-up countries.

In the second method, however, I measure the degree of error at the level of assignees. In other words, I calculate the percentage of patent applications in which inventor and applicant are the same for each assignee. The second method could help us to complete the inventor country just for those assignees which have high percentage of inventions in their own country of application. In other words, for those assignees where a high percentage of their inventions has been registered in their own countries, this completion process would be followed. In contrast, if some assignees do most of inventions outside of their attributed countries, we could not simply guess the country of invention from assignee countries when it is unknown. The threshold for the application of this method could be chosen at different percentages. The table temp.17 (in my dataset) is the list of PATSTAT assignees in upstream petroleum industry and the probability of each assignee to register a country as the location of inventor if its inventions attributed to that country as the assignee country. The threshold which set for this study is explained later where I describe the completion process of country of invention of the patent families.

3- Main invention country of applicants as the source

The degree of confidence for this method of estimation varies from company to company and is highest for local companies and lowest for international companies. The more the international inventive activities of the companies, the less reliable the estimation of invention country with main invention country. For example there are some very international companies where just below 50 percent of their patents are invented in their home country. Given the fact that the lions share of innovations are controlled by international companies, this method is reliable more in their main country of invention. Nonetheless, this estimation is not problematic for this study even in the case of multinational companies. This is because in the worse situation we attribute the international inventive activities of multinational companies to their home country where they usually run majority of their innovative activities. Given the fact that our aim is to analyze catch-up processes, this seems realistic to attribute the international innovative activities of multinational companies to their home country rather than the host country. This is because these technological capabilities are in fact the knowledge assets controlled by the parent company.

Completion of missed countries using above sources:

The total number of application-inventor' combination is 514674 of which 266675 have a known invention country from the original PATSTAT database. These are equivalent to a total number of 115104 patent families of which 56944 have a known inventor country. Given the high degree of reliability of first method when combined with second method (using priority country as the invention country when agrees with assignees' country), I first applied this method. 112390 more application-inventor combinations are assigned a country, which is equivalent to 35084 patent families.

In the second stage I applied the second source, selecting the assignee country as the country of invention but just for those assignees which their country is 100% the same as country of invention. In other words, applicants' country is replaced as invention country for those applications whose applicants do all of their inventive activities in the same country according to our dataset. This process has completed 10586 more application-inventor which corresponds to 5247 families.

Table A-3 Completion of missing country data by different sources

Completion stage	Application -inventor	Unique families (% of total)
Original	266675	56944 (49.4%)
Stage 1	112390	35084 (30.4%)
Stage 2	10586	5247 (4.6%)
Stage 3	33688	18674 (16.2%)
Stage 4	6687	1833 (1.6%)
Stage 5	9371	3329 (2.9%)
Complete numbers	439397	102548 (89.1%)
Missed	75277	12556 (10.1%)
Total	514674	115104 (100%)

In the third and fourth stage, I used the combination of the first and third method to increase the degree of reliability. From our data we know that applying only the first method (priority country) might have about an 8 percent error. If combined with main invention country information, the error should be reduced. Suppose an international company does innovative activities in several countries including its home country which is its main invention country. The probability that for innovations performed in the home country, the patent is applied first in the home country is higher, compared to innovations performed abroad which might applied for their patents either from local patent authorises or international routes.

Given the fact that the main country of invention could be produced both for Derwent and PATSTAT assignees, we could use this source from both databases. Therefore for the third stage I replace invention country with priority country when is the same as the main invention country, based on Derwent assignees. The fourth stage is the same as the third stage but PATSTAT assignees have been used to match priority country with main invention country of assignees. Applying these stages respectively 33688 and 6687 application-inventor combination have been assigned a country of invention which correspond to 18674 and 1833 unique patent families.

In the fifth stage, the third method has been applied. It means that for 9371 application-inventor combinations which correspond to 3329 unique families, the main country of invention of Derwent assignees has been attributed as invention country. The summary of this completion process is shown in the table A-3 where we have 102548 patent families, which their country of innovation is known or estimated. All geographical analysis of patters of innovation has been based on this final completed table in this study, when inventors’ country is meant to be used.