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LATECOMER FIRMS AND THE DEVELOPMENT OF KNOWLEDGE NETWORKS: THE CASE OF PETROBRAS IN BRAZIL

Abstract

This paper addresses the development of knowledge networks within learning and innovation systems in late industrialising countries. It examines the development of a firm-centred knowledge network in the case of Petrobras, the Brazilian oil company, over more than thirty years between the late-1960s and the early-2000s. The paper demonstrates that there were continuous shifts in the properties of Petrobras' knowledge networks through time. There was a clear trend in the properties of knowledge networks to evolve towards increasing intentionality, complexity, diversity and complementarity. A key contribution of the paper is also conceptual and methodological: the development and operationalisation of an original typology of knowledge network properties and its application in conjunction with retrospective historical methods to track out organisational evolution over the long period since the late-1960s.

Key words: knowledge networks, innovation systems, late-industrialisation.

1. Introduction

The analysis of technological learning in latecomer economies has shifted over recent years from the study of capability building in individual firms, the focus of research in the 1980s and 1990s, to examine the development of learning and innovation systems. Broadly, this new direction of work has addressed four main components, or 'building blocks' (Malerba 2004), of innovation systems: (i) the main organisational actors (firms, universities, scientific and technological institutes, etc.) and their capabilities, (ii) the knowledge-centred and other interactions between these actors, (iii) the technologies used and produced by the actors, and (iv) the institutional contexts and policy environments within which that use and production of technology takes place.

In this paper we briefly concentrate on the first two of these building blocks (specifically, on firms as the key actors and on knowledge-centred networks as their key interactions). After that the bulk of the paper focuses on the second building block (knowledge networks) because this seems to be the system component that has been most neglected in studies of learning or innovation systems in latecomer economies. However, we recognise well that this focus abstracts from important relationships among the main components, and we will re-locate our knowledge network study back into its wider system framework at the end of the paper.

The importance of understanding the dual development of both capabilities in enterprises and knowledge-centred networks within which they are embedded became increasingly clear as several studies in even quite mature late-industrialising economies highlighted the existence of constellations of firms that neither had very innovative capabilities (e.g. Arocena and Sutz 2000, Viotti 2002) nor were embedded in well articulated knowledge-networks – for example Intarakumnerd *et al.* (2002) in Thailand or Lastres *et al.* (2003) in Brazil.[1] In other words, these constellations seemed to demonstrate neither of the necessary properties of innovation systems – innovativeness and 'system-ness.'

There have been numerous studies of various aspects of that situation in industrialising economies but they have been fairly limited in scope. Most have involved static analyses of the current characteristics of innovation systems, and only a few have addressed issues about whether and how aspects of innovativeness and/or 'system-ness' emerge and change over time as part of a development process. Among the latter a very small number have shown some development of one or both of these system characteristics – e.g. Wong (2003), Amsden and Chu (2003) or Kim and von Tunzelmann (1998). More often the picture has been 'negative', with observations suggesting that such paths of development have been absent, limited or even reversed – e.g. Hou and Gee (1993), Kim (1993), Alcorta and Peres (1998), Liu and White (2001), Lall and Pietrobelli (2002), Lemos *et al*. (2003), or Szapiro (2003). Thus, so far a body of largely static and generally 'negative' observations has been accumulated. This provides a very limited basis for comparative analysis of the processes involved in the development of differing and changing system structures and behaviours.

[1] Lastres *et al*. (2003) found this such a common feature across several areas of production in Brazil that they coined the term "local productive arrangements" to refer to "productive agglomerations in which there is no (or almost no) articulation among the agents and which, therefore, could not be considered as systems" (p.23).

[2] In other circumstances this alignment may not be evident, and the combination of forms of the different properties may not fall so neatly into the column structures of the table.

[3] We examine that interaction between capabilities and network development in another paper (Dantas and Bell 2006), and we comment very briefly on it at the end of this paper.

[4] Although we have not been able to present the necessary detail in this short outline, this development did not follow a completely linear process; nor was the pattern identical across different technologies at particular times.

[5] See also Figueiredo (2001) for a similar demonstration of long-term retrospective methods in tracking the accumulation of internal capabilities in individual firms.

Two further limitations of this body of work have centred more specifically on the knowledge network component of innovation/learning systems. One has been about the boundaries typically drawn around the networks. In one sense there has been considerable diversity in this: studies have examined knowledge interactions among actors in regions, clusters, industries and countries. But in another sense, except in studies of knowledge flows between actors in global value chains or global production networks, the bounds of knowledge networks have been quite restrictive: typically being set at national borders. This neglects the importance of inter-country knowledge links and excludes the development of understanding about how these change over time.

A second limitation is probably more important: the conceptual framework for the comparative analysis of knowledge networks remains weak. This contrasts with research on the accumulation of innovative capability in individual enterprises, where systematic typologies and frameworks have existed for a considerable time (e.g. Lall 1992, Bell and Pavitt 1995, Figueiredo 2001). As yet however, only tentative steps have been taken towards the development of structured conceptualizations of differences and changes in the properties of knowledge networks in late-industrialising contexts.

One such step was taken by Mytelka and Farinelli (2003) who, stressing the importance of knowledge-centred interactions for innovation in clusters, refer to the movement “from simple spatial agglomerations to dynamic innovation systems” (p.252), and then outline a typology of characteristics by which one might trace such movement between clusters that are successively ‘informal’, ‘organised’ and ‘innovative’. However, among the 11 system properties used in the typology, only one refers to knowledge-links and only two categories of these are identified: “some” and “extensive” (p. 254). Bell and Albu (1999) take things a bit further in outlining a taxonomic framework for assessing the dynamic evolution of knowledge systems in clusters in developing countries. They incorporate several aspects of knowledge flows (e.g. their passive/active origins, horizontal/vertical directions, and internal/external sources), and discuss how these and other properties may shift as system structures evolve from “unstructured, passive and closed” forms towards those that are “structured, active and open”. However, such outlines are sketchy and conjectural and have not been applied in any empirical analyses of the evolution of innovation systems in developing countries.

This paper addresses these limitations. It examines a firm-centred knowledge network, without any spatially defined bounds, providing a ‘positive’ case study of the extensive development of knowledge networks in offshore oil technologies by the Brazilian company, Petrobras. It also applies an original taxonomy of the properties of knowledge networks to a longitudinal study tracing the development of the company’s knowledge networks over more than thirty years between the late 1960s and the early 2000s. The paper is organised as follows. Section 2 presents the taxonomic framework used in the study. Section 3 outlines other aspects of research design and method and Section 4 presents the empirical evidence. Section 5 summarises the conclusions of the paper.

2. The Development of knowledge networks: a framework for analysis

Based on Orsenigo *et al*. (2001:485-486) knowledge networks are defined here as organisational arrangements that involve actors with different capabilities and that are concerned with knowledge flows and the coordination of learning and innovation: they involve the *acquisition*, *combination*, *generation*, *exchange* and *transfer* of complementary and heterogeneous forms of knowledge. The idea of 'developing' such networks is defined in dynamic terms to encompass not merely the one-off initiation of a particular set of interactions but the longer term process by which further interactions are put in place, perhaps involving changes in the properties of those networks over time.

Two sets of properties of networks have attracted most interest. One is concerned with their spatial configuration, frequently concentrating only on the parts of networks that fall within cluster, regional or national boundaries. This paper does not address that set of characteristics. Instead it focuses on a second set concerned with the cognitive properties of networks. More specifically, drawing on the literature about networks, linkages and capabilities, our analysis of network development concentrates on the following five selected properties (see Table 1):

i) the intentionality in decision-making underpinning the development of the network, distinguishing it in terms of degrees, ranging from less to more explicit and deliberate intent to develop networks for technological accumulation;

ii) the nature of technological accumulation activities with which the network is concerned, decomposing it according to the level of complexity and the diversity of technological accumulation activities that simultaneously occur in the network;

iii) the content and direction of knowledge flows contributing to further technological accumulation, organised by levels of complexity and diversity respectively;

iv) the sources of knowledge flows, classified according to their diversity in the network;

v) the division of labour in knowledge production between the core nodal player and its partners, differentiating it according to the diversity and complementarity of coordination arrangements present in the network.

Table 1 Selected properties of knowledge networks

Properties	**Varying Forms of Properties**			
	A	**B**	**C**	**D**
i) Intentio	Passively engaged in the	Actively centred on	Actively centred on using networks to	Strategically centred on using networks as

nality underlying the development of the network	acquisition of knowledge via networks largely as a by-product of activities with other objectives	using networks to achieve learning objectives	achieve innovation objectives	devices to access distributed capabilities located outside the firm's organisational boundaries
ii) Technological accumulation activities with which the network is concerned	Acquisition and assimilation of goods, services and operational know-how	Adaptations of technologies. Learning and absorption of design and S&T knowledge underpinning technologies	Innovation/development of technologies. Absorption of S&T knowledge in novel technologies	Innovation/development of technologies. Reverse transfer of technology to partners. Exchange of technology. Absorption of S&T knowledge in novel technologies
iii) Content and directions of knowledge flows	Unidirectional and bidirectional flows of operational knowledge	Predominantly unidirectional flows of design and S&T knowledge	Predominantly bidirectional flows of design and S&T knowledge, but also unidirectional flows of design/S&T knowledge	Combination of bidirectional, unidirectional and reverse unidirectional flows of design/S&T knowledge
iv) Sources of knowledge	Suppliers of goods and services	Suppliers, S&T organisations, competitors	Suppliers, S&T organisations, competitors, and nodal player itself	Suppliers, S&T organisations, competitors, increasing importance of nodal player itself
v) Division of labour in knowledge production between the nodal player and others	Asymmetric – with key knowledge-producing activities externally located in network partners	Increasing participation in knowledge production but via asymmetric arrangements	Symmetric and specialised knowledge production between nodal player and partners, but also asymmetric external	Combination of symmetric specialised knowledge production, asymmetric internal and asymmetric external
Overall patterns	**Passive learning networks**	**Active learning networks**	**Innovation networks**	**Strategic innovation networks**

Source: research findings and literature on networks, linkages and capabilities.

Key – S&T: scientific and technological or science and technology

Each of these cognitive properties can assume different forms, perhaps changing between them through time. These different forms are classified here into four categories for each of the cognitive properties, and they are aligned in the four columns under (A) to (D) in Table 1. In the case of Petrobras, the categories were closely associated across the five properties, and it makes empirical sense to assign summarising terms to the combination of forms in each column – as shown in the bottom row of the table.[2]

At one extreme (column A) the combination of forms is summarised as a '*passive learning network*', involving (i) passive intentionality in decision-making underpinning the development of the network, (ii) an emphasis on accumulating technology through networking in the form of goods services and operational know-how, (iii) unidirectional and bidirectional flows of operational knowledge, (iv) suppliers as the primary sources of knowledge flows in the network and (v) a highly asymmetric division of labour in knowledge production.

At the other end of the spectrum (column D), the combination of forms is summarised as a '*strategic innovation network*', characterised by (i) strategic intentions to use networks to access and coordinate capabilities that are distributed outside the boundaries of the firm, (ii) technology accumulating activities occurring through a combination of several types of complex activities, (iii) knowledge flows with much greater directional diversity and involving complex design/S&T types of knowledge, (iv) sources of knowledge in a wide range of different kinds of organisation, including the nodal firm itself, and (v) diverse and complementary combinations of symmetric and asymmetric divisions of knowledge labour between the nodal player and partners.

An array of network forms exists between these extremes, classified into two categories here under columns (B) and (C). However, our indication of the possibility of knowledge networks evolving between Columns (A) and (D) involves no presumptions about optimality or linearity. There is no archetypical ideal network for all firms or industries, and evolution is not presumed to follow any particular linear path through Table 1.

3. The empirical context

Petrobras is the Brazilian state-controlled oil company and a major player in the international offshore oil industry particularly in deep and ultra-deep water operations. Petrobras was created in 1954 to impose state monopolisation on exploration, production, refining and bulk transport, but not distribution, and it became the main player in the emerging Brazilian oil industry. At the time of Petrobras' inception, Brazil's oil production was just 2,700 bbl per day (Petrobras 1994:13-14) and in 1955, the proportion of national production in total domestic consumption was 7.34% (Dantas 1999:84).

The initial emphasis in the investments of the company was on oil importing and refining.

The share of upstream investment expenditure in total investments between 1960 and 1970 remained at around half of the total investments of the company, sinking to as low as 24% in 1971 (Cf. Dias and Quagalino 1995:135). Nevertheless, there was considerable development in onshore production in Petrobras' first decade with domestic production in 1961 reaching 95,000 bbl per day and accounting for 35% of national consumption (Furtado 1995:164).

As existing onshore reserves declined, the company increased its exploratory efforts on the continental shelf which led to the eventual discovery of the Guaricema field in 1968, and several other fields thereafter, off the Brazilian Northeast coast. In 1974, major oil reserves were discovered in the Campos Basin, off the coast of Rio de Janeiro state, which was to become the most prolific oil producing area in Brazil. With the intensification of offshore activities in the Campos Basin during the late 1970s and 1980s, the share of production in consumption had reached the 50% threshold by 1985 and proven Brazilian oil reserves climbed to 1.3 billion bbl by 1980 (Furtado 1995:166, 122).

During the period from the 1970s to the early 1980s, there were major shifts that contributed to consolidating offshore production. Following the first oil crisis, in a context of high oil prices and difficulties in the Brazilian balance of trade, expanding national production became a priority. There was an increase in the share of investment in exploration and production (E&P) in the total investment expenditure of Petrobras from 24% in 1971 to around 83% in 1985 (Cf. Dias and Quagalino 1993:135). Petrobras' production capacity increased from 180,000 to 563,000 bbl per day between 1980 and 1985 (Cf. Furtado 1995:166) and in 1982, for the first time offshore production overtook onshore production accounting for 54% of total production (Freitas 1999:82).

From 1984 Petrobras came to face unique technological demands associated with the nature of the Brazilian offshore reserves and this, together with Petrobras' institutional role, strongly shaped the subsequent technological development of the company and to certain extent the offshore oil industry in general. In 1984 and 1985, Petrobras discovered giant deep water oil fields in the Campos basin. These fields were located at depths of up to 2,100 m, with the majority of oil resources located in deep waters (> 400 m). The Brazilian debt crisis in 1983 had given urgency to the need to increase national production and save foreign currency. However, Petrobras found itself in the unique situation that the technologies needed to exploit those deep water resources were not available in the international market. Moreover, after the collapse of oil prices in 1986, there was a de-investment in deep water projects in other offshore provinces around the world. Thus, it became clear for Petrobras that, because of its institutional role, it could not afford to wait for the major oil companies and international suppliers to develop these technologies in their own time. Its nationalist-developmental objectives led the company to make considerable efforts to catch up technologically, and subsequently to forge ahead with the development of deep water technologies in order to be able to increase national production. By the early to the mid 1990s, Petrobras was playing a leading role in the international industry in creating and applying totally novel technologies for deep water conditions and breaking repeated world records in production and drilling water depths.

The late 1990s and early 2000s was a period of great changes in the Brazilian offshore oil industry, and saw the end of Petrobras' monopoly in 1997. As a result of this, the major international oil companies started operating in Brazil. In the early 2000s, Petrobras was ranked overall as the 12th largest oil company according to the ranking by Petroleum Intelligence Weekly of the world's 50 largest oil companies, based on operational data from 2000 (Petroleum Intelligence Weekly 2001). Petrobras' oil production in 2001 was 1.35 million bbl per day, with around 60% coming from deep and ultra-deep water fields, making Petrobras the world leader in deep water production.

4. Research design and method

The use of a single case study centred on Petrobras to analyse knowledge network development stemmed from two considerations. First, as noted above, studies of knowledge networks in late industrialising countries have mostly focused on their weaknesses or absence. Consequently the examination of a more positive experience would, we believed, contribute more to new understanding; and the case of Petrobras, the state-company in the Brazilian offshore oil industry, was selected because previous research indicated that it had built a wide set of linkages with external sources of knowledge (e.g. Dantas 1999, Freitas 1999). Second, the need to analyse network development over a reasonably long period of time and to collect data from multiple sources in order to address problems about recollection and other errors among respondents made it impractical to examine network development from the perspective of multiple network members. Consequently, we focused the research on the Petrobras-centred knowledge network in offshore technologies, examined from the perspective of that focal firm itself.

Investigation of that network was based on the integration of data about 14 different offshore technologies in order to provide a reasonably representative sample of the wide spectrum of technologies involved in the company's offshore operations – see Table 2. This allowed us to draw a composite picture of the changing structure of the company's overall knowledge network concerned with offshore technology.

Table 2 The technological scope of the case study

The sample of technologies covered			
(1)	Semi-submersible platforms	(8)	Instrumented pigs
(2)	Fixed platforms	(9)	Multiphase pumping systems
(3)	Wet Christmas trees	(10)	Atmospheric well-head cellars
(4)	Flexible flowlines and risers	(11)	Seismic-stratigraphy
(5)	Umbilicals	(12)	Analysis of turbidite formations
(6)	Basin analysis and modelling	(13)	Remotely operated vehicles
(7)	Well technologies and drilling	(14)	Control systems

The main body of data was collected through 114 semi-structured interviews with the focal company and other organisations. These provided information about the history of collaborations in each of the fourteen technology areas. In addition, information was collected through informal meetings with key individuals and from documentary sources. The analysis of the data fell into three stages.

First, a set of four time periods was identified. These reflected stages in the company's development corresponding to shifts in key characteristics of the Brazilian offshore oil industry. The first phase started with the initial offshore operations by Petrobras in the late 1960s and concluded with the deep-water discoveries in 1984. The second phase (1985-1991) covers Petrobras' first formalised programme of technological capability development. The third (1992-1996) corresponds to the last years of the monopoly of Petrobras, and the fourth runs from the end of Petrobras' monopoly in 1997 through the initial transition to liberalisation in the early 2000s.

Second, the records of interviews and other data were converted into analytical data displays based on the framework in Table 1. The information was collapsed to a number of indicators associated with each of the network properties for each of the 14 technology areas and four time periods, and the indicators enabled the network properties to be classified in terms of the categories in Table 1.

Then third, the data displays were analysed using several approaches. Commonalities and discrepancies in network properties associated with different technologies and time periods were identified. Further data displays were built to move the analysis from individual technologies to aggregate views and composite syntheses of network properties for Petrobras as a whole at different times. The data were thus reorganised into an analytical chronology.

4. Petrobras' knowledge network: from passive learning to strategic innovation

With respect to the technologies for its offshore operations, Petrobras moved through two linked transformations between the late 1960s and the early 2000s. On the one hand its internal capabilities shifted dramatically from those of an imitative technology-user to those of a leading player at the international innovation frontier. On the other it transformed its knowledge network from what we summarise as a passive learning network to a strategic innovation network. Although they interacted closely, we examine here only the second of these transformations.[3]

We do so through Section 4.1 to 4.4 with respect to each of the four periods outlined earlier. However, an important pattern is that the forms of network properties were not uniform in each period. Instead, two patterns were evident during all periods except the last. The first involved the consolidation of particular forms into those that were dominant and pervasive during the period. The second was the emergence of new forms in a few selected areas of technology, usually arising towards the end of a period. These successive developments are summarised in Table 3.

Table 3 The development of Petrobras' knowledge network

Network Properties	**Late 1960s to 1984**		**1985 to 1991**		**1992 to 1996**		**1997 to early 2000s**
	Dominant	**Emerging**	**Dominant**	**Emerging**	**Dominant**	**Emerging**	**Dominant**
i) Intentionality underlying the development of network	Passive	Active for learning	Active for learning	Active for innovation	Active for innovation	Strategic	Strategic
ii) Technological	Acquisition and assimilation of goods, services and operational know-	Learning and absorption of design and S&T knowledge underpinning techno	Learning and absorption of design and S&T knowledge underpinning technologies.	Innovation and absorption of S&T knowledge in novel concepts	Innovation and absorption of S&T knowledge in novel concepts	Transfers of technology to partners Exchanges of technology	Innovation. Absorption of S&T knowledge in novel concepts. Transfe

accumulation activities with which the network is concerned	how	logies/ Adaptations		Hybrid innovation for learning						rs of technology to partners. Exchanges of technology
iii) Content and directions of	Unidirectional and bidirectional flows of operational knowledge	Predominantly unidirectional flows of design and S&T knowledge		Predominantly unidirectional flows of design and S&T knowledge	Predominantly bidirectional flows of design and S&T knowledge		Predominantly bidirectional flows of design and S&T knowledge, but also unidirectional flows from partners to nodal	Reverse unidirectional flows of design and S&T knowledge		Combination of bidirectional, unidirectional and reverse unidirectional flows of design and S&T knowledge

knowledge flows enhancing capability accumulation					firm.		
iv) Sources of knowledge flows	Predominantly suppliers	S&T organisations	Suppliers; S&T organisations; competitors	Petrobras itself	Suppliers; S&T organisations; competitors; Petrobras itself	Increasing importance of Petrobras	Suppliers; S&T organisations; competitors; and increasing importance of Petrobras
v) D	Asymmetric knowl	Increasing partici	Increasing	Symmetric	Symmetric special	Asymmetric	Symmetric

ivision of labour in knowledge production	edge production with key knowledge-producing activities external in partners	pation in knowledge production via mostly asymmetric arrangements	participation in knowledge production via mostly asymmetric arrangements	specialised knowledge production between nodal player and partners	ised knowledge production between nodal player and partners, but also asymmetric external	knowledge production with key knowledge-producing activities internal in the nodal player	specialised knowledge production,but also asymmetric internally- and externally-driven knowledge production
Overall patterns	**Passive learning networks**	**Active learning networks**	**Active learning networks**	**Innovation networks**	**Innovation networks**	**Strategic innovation networks**	**Strategic innovation networks**

Source: research findings

4.1 The late 1960s to 1984: from a passive towards an active learning network

With the beginning of Petrobras' offshore operations, an embryonic knowledge network in offshore technologies started to take shape around the company. The dominant pattern that was consolidated during this period consisted of a passive learning network. It was characterised by the following forms of the various network properties.

In terms of the intentionality underpinning the development of the networks, Petrobras had no explicit, active intention to engage in network relationships in order to achieve objectives about learning or innovation. Its main rationale for interacting with other organisations, particularly foreign suppliers and later the subsidiaries of foreign suppliers that were set up in Brazil during the late 1970s and early 1980s, was to identify and acquire equipment and services according to the company's operational needs. Learning outcomes and flows of knowledge were passive by-products of the transfer of these goods and services.

The firm's technology accumulation activities within networks were centred on the assimilation of acquired methods, equipment, services and operational know-how. For example, in 1977, the company established a technical assistance contract with a service supply company, Sedco-Hamilton, to acquire an emerging technology for offshore production, the newly-devised floating production system, which was based on a drilling semi-submersible platform converted to production. In 1978, Petrobras interacted with Vetco, an American supply company, to obtain the first wet Christmas tree to be installed in Brazil in the East Enchova field. Petrobras continuously interacted with supply firms in order to obtain offshore technologies and continuously introduce new vintages of equipment based on its specific requirements associated with the need to operate in increasingly deep waters.

The flows of knowledge were restricted to operational knowledge and the main sources of knowledge were supplier firms, while few other organizations played a significant role in the network. The flows of knowledge were for the most part one-way as Petrobras worked closely with its supplier in acquiring detailed knowledge about the characteristics of equipment and its operation. However, these unidirectional flows were soon followed by two-way flows as Petrobras began to participate in the production of operational knowledge for its suppliers in connection with technical bottlenecks, equipment performance, trouble-shooting activities and required improvements. For example, in flexible lines and risers, on the one hand, Petrobras obtained from Coflexip, a French supplier firm, detailed information about the characteristics of the flexible lines and what was known about the behaviour of the flexible risers operating in dynamic conditions in floating platforms, their durability, resistance, and limitations. On the other hand, Petrobras continuously updated Coflexip with empirical knowledge about the operational behaviour of flexible risers and lines that was discovered in the course of the installation and operating procedures, and with information about operational problems that needed to be addressed through re-design and re-calculation of the design parameters of the equipment; it identified further requirements to adapt the equipment for application in ever deeper waters.

The division of labour in knowledge production between Petrobras and the other network actors was sharply asymmetric and clear-cut. Key research, development and design activities were externally located in suppliers. Petrobras participated in the production of knowledge through the generation of operational knowledge through equipment operation and trouble-shooting activities. For instance, in 1979, the company adopted a complex dry subsea system based on the use of atmospheric well-head cellars, supplied by Lockheed. Lockheed carried out the development of the atmospheric well-head cellars, and the first use of the technology in the world was in Petrobras' Garoupa and Namorado project. The installation and operation of the atmospheric system proved to be problematic; the new system demanded continuous interventions. Petrobras' first hand operational experience generated data about the factors that needed to be corrected, which were then fed back to Lockheed.

However, as this dominant pattern became consolidated, new forms of properties associated with an active learning network started to emerge: in a number of technology areas the company's decision processes came to be characterised by active intentions to use networks more explicitly to achieve objectives concerned with learning. The emphasis was on the accumulation of design and S&T knowledge bases underlying offshore technologies, and also on undertaking joint adaptation activities. The company also started to extend its participation in knowledge-production. For example, it adopted technology transfer arrangements whereby it learned from suppliers to do more complex technological activities or entered collaborations with domestic equipment suppliers to adapt equipment. The external knowledge sources that were drawn into these new forms of knowledge network began to include not only suppliers but also foreign and local universities such as the University of Texas at Austin, the University of Illinois, the University of Paris, the Federal University of Bahia (UFBA), and the Federal University of Ouro Preto.

4.2 From 1985 to 1991: consolidating an active learning network and the emergence of an innovation network

During this phase the company's knowledge network went through a major change as the properties of an active learning network that had begun to emerge in the previous period were consolidated pervasively across technologies. This involved the following main features.

The company had a much more active and pervasive intention to use knowledge networks to achieve learning-related objectives, not merely to acquire knowledge passively as a by-product from purchasing goods and services and operating know-how as in the previous period. Petrobras decided to enter knowledge networking at this stage to learn about and internalise the design, and S&T knowledge through the collaborations – rather than to co-develop innovative applications – in order to pursue independent knowledge-producing activities related to R&D, in the future. Petrobras' main aim was to reach a degree of self-sufficiency in technological development (Petrobras 1998a:29).

The focus on technological accumulation activities within networks shifted pervasively from the assimilation of goods, services and operational know-how towards the accumulation of design and S&T knowledge underlying the technologies to be used. These technological accumulation activities occurred within collaborative arrangements such as engineering consultancies, technical assistance projects, participation in joint industry projects, inter-organisational movement of technical personnel and collaborative training programmes. For instance, in the mid 1980s, Petrobras interacted with the Graduate School and Research in Engineering (COPPE) to gain knowledge in design of semi-submersible platforms. COPPE carried out a study of the existing designs of semi-submersible platforms and prepared a handbook for Petrobras with an analysis of the normal configuration designs and design criteria and parameters of such platforms. They also entered technical assistance agreements in the late 1980s to learn to master basic design activities, with the Swedish company, Gotaverken Arendal AB (GVA). This allowed them to acquire the semi-submersible platform designs, and to absorb the design procedures to allow them at a later date, to carry out the basic design of the platform independently. Also in the late 1980s, Petrobras collaborated with Chalmers University in Sweden to draw on knowledge flows and obtain design tools for the naval and structural designs of the semi-submersible platform. In addition, Petrobras also interacted with the certifying company, Det Norske Veritas (DNV), not only to certify the platform design, but also to draw on design knowledge flows and learning to carry out design work. In contrast with the previous phase where the emphasis was on the flows of operational knowledge, now the content of knowledge flows, as this example illustrates, involved more complex design and scientific knowledge, whereas the direction of these design and S&T knowledge flows remained predominantly unidirectional from partners to Petrobras.

As indicated by the experience above, there was also a clear shift in the division of labour in knowledge production in relation to the previous phase. Petrobras was interested to participate more in knowledge production, beyond that occurring solely through operational activities, though during this phase this still happened within a significantly asymmetric division of labour in which Petrobras learned from partners.

Another marked shift was in relation to the sources of knowledge flows in Petrobras' networks. The origins of knowledge flows continued to diversify away from being solely supplier firms towards a wide range of other actors. These included universities, research institutes and other oil companies. In well technologies and drilling, for instance, Petrobras joined several joint industry projects, including one with Marathon Oil to draw on knowledge flows on control of sand production in directional drilling and one with Smedvig, a Norwegian oil and contractor company to obtain knowledge on subsea drilling, completion and work-over operations. In 1986 Petrobras also started a collaboration with the Pontifical Catholic University of Rio de Janeiro (PUC-Rio) to develop a Masters programme in rock mechanics and drilling. This Masters programme gave Petrobras' participants an understanding of the mechanical principles associated with rock and well stability, and the behaviour of rocks during drilling activities. In addition, Petrobras had close contact with the University of Oklahoma, and sent its technical personnel for PhD training in rock mechanics.

One consequence of the combination of active learning efforts and increased participation in knowledge production was that, in a few cases, the knowledge networks were hybrid in form – that is, established partly with a view to generating innovative equipment for new deep water conditions, but primarily and more importantly as learning vehicles to build up R&D capabilities. This happened, for instance, in the case of collaborations between Petrobras, a Brazilian supply company, Consub, COPPE and PUC-Rio in remotely operated vehicles. These networks involved joint R&D activities and learning by trial and error; and some knowledge design flows between the company and suppliers were bidirectional, but flows from Petrobras were more usually limited and the participation of the company in knowledge production was restricted.

Nevertheless, towards the end of this period in a few technological fields the company started moving to new forms of interaction that were explicitly intended as mechanisms for undertaking innovation. In these areas the properties of the knowledge network started changing towards those of an innovation network – involving bidirectional flows of design and S&T knowledge and increasingly balanced and complementary arrangements for joint knowledge production as the company established collaborative R&D with universities and research institutes to generate new technologies and scientific knowledge. This happened, for instance, when Petrobras interacted with PUC-Rio and the Institute for Technological Research (IPT) to generate knowledge about well technologies, particularly in rock mechanics and the development of computer simulators for predicting sand production in wells located in unconsolidated reservoirs.

4.3 From 1992 to 1996: consolidating an innovation network and moving to a strategic innovation network

During this phase, Petrobras' knowledge networks changed yet again as the company consolidated the innovation network properties that had started to emerge in the last stages of the previous period. Although this transition was not automatic across all technologies, the following features became widespread and important.

An active intention to use knowledge networks to achieve innovation-related objectives became pervasive. In the process of internalising an initial stock of S&T understanding of offshore technologies in the previous period, the company realised that it was unsustainable to hold in-house all the S&T knowledge bases relevant to exploration and production technologies. Petrobras recognised that it was more important to engage in partnerships for complementary developments. Petrobras believed it had reached a high level of technical capabilities and was ready to use these capabilities "to join synergetic collaborations with partners both in Brazil and abroad" (Petrobras 1998:29-30).

The nature of technological accumulation activities within networks consistently evolved to become centrally concerned with innovation-related objectives and the flows of design-related and S&T knowledge became pervasively bidirectional. Petrobras pursued repeated collaborations for joint incremental innovation with suppliers, such as Cameron, ABB-Vetco Gray, Flexibras and Coflexip in fields of proven technologies such as wet christmas trees, risers, flowlines, manifolds and umbilicals. Petrobras also established collaborations characterised by bidirectional S&T knowledge flows to develop applications of concepts that were novel not only to the company, but also to the industry to accelerate shifts in technological trajectories. For instance, the company entered collaborations with Bornemann and subsequently with Westinghouse and Leistritz for the development of a multiphase pumping system. However, in addition, the networked innovative efforts of the company also included the participation in collaborations coordinated by other organisations and involving unidirectional flows of S&T knowledge from the main executor of the project to Petrobras – for instance, when Petrobras engaged in joint industry projects led by the Imperial College, the UK National Engineering Laboratory and Texaco to monitor the development of different concepts of subsea multiphase flow meters.

These innovation-centred interactions were characterised by an increasingly symmetric division of labour in knowledge production, but also complemented by asymmetric arrangements in which key R&D activities were externally located in network partners. In the collaborations for joint incremental innovation and to joint develop major innovations and novel concepts, Petrobras co-ordinated the projects and the company and each partner carried out specialised and complementary R&D activities in symmetric arrangements. For instance, in instrumented pigs, in a collaboration with PUC-Rio to develop a magnetic pig, Petrobras developed the magnetic sensors and mechanical design and PUC-Rio developed the electronics, the electric part, and the software. In asymmetric arrangements, mainly through the participation in joint industry projects, Petrobras participated as a co-sponsor of the R&D efforts coordinated and executed by leading organisations in offshore technologies and gained access to the results of the project. This happened, for example, in rock mechanics and wellbore stability, when in 1992, the company joined the Rock Mechanics Consortium established by the University of Oklahoma.

As with the learning-centred linkages in the previous period, these innovation-centred collaborations involved a wide range of actors as sources of knowledge in the networks, such as S&T organisations, other oil companies, and supplier firms. However, a significant change in relation the previous period was the increasing participation of Petrobras as an important source of S&T knowledge to its network partners.

But beyond these kinds of consolidation, new network features emerged by the end of this period as the company began shifting towards more strategic innovation networks in a few technology areas. Knowledge networks were increasingly seen by Petrobras as a strategic asset allowing access to complementary distributed capabilities located outside the boundaries of the firm. In this context, the growing importance of Petrobras as a source of knowledge at the international technological frontier for international oil companies and suppliers was a key element in securing access to these complementary capabilities. Petrobras started to establish not just bidirectional technology exchanges with competitors and suppliers, but also collaborative arrangements involving reverse unidirectional technology transfers to suppliers. In these arrangements the company internalised the key R&D activities and design activities for new equipment, outsourcing only its production via the transfer of its own original designs to a partner. The collaboration from 1994 with a Norwegian company, Kvaerner, in the development of Petrobras-designed wet christmas tree is an example where the company became an important source of unidirectional flows of design knowledge for foreign partners. New forms of interaction were also established with other oil companies in which in-house expertise in selected technological fields was exchanged for the expertise of other oil companies in other technologies. In 1994, for instance, Petrobras signed technology exchange agreements with Shell to exchange its knowledge in semi-submersible floating production systems with Shell's expertise in tension leg platforms, and with BP and Statoil in floating production systems.

4.4 From 1997 to the early 2000s: the consolidation of a strategic innovation network

During this period, Petrobras moved on to consolidate the emerging properties of strategic innovation networks that were identifiable in the previous phase. A major change was the increasingly strategic intention driving the development of networks. In the previous phase, Petrobras' main intention had been to use collaborations to generate joint innovations. However, in this period Petrobras became aware that it possessed knowledge bases that were attractive to other companies. Conversely, Petrobras increasingly recognised that key capabilities and expertise relevant for the company's innovative activities were in fact located outside its organisational boundaries. Thus, Petrobras saw knowledge networks as strategic devices to access and mobilise these distributed capabilities wherever they were located.

Technological accumulation activities within networks continued to evolve to include new forms during this last period, and the directions of knowledge flows became correspondingly diverse. Two-way of complex design/S&T knowledge continued in what had become by this time 'conventional' joint innovation-centred collaboration arrangements to develop incremental changes in existing technologies or to generate novel technologies and trajectories. Inward one-way flows of S&T knowledge associated with Petrobras' participation in other organisations' innovative projects to monitor the frontier also continued to be a common feature. But the most striking shift during this last period was the increasing use of new forms of relationships with other organisations concerned with reverse technology transfers in which Petrobras itself was the main source of unidirectional flows of complex S&T knowledge to partners, thus reversing the direction of the earlier one-way flows. As one example, Petrobras established in the late 1990s a joint industry project in collaboration with Fluenta in subsea multiphase flow meters. Petrobras led the project and was in charging of executing key R&D activities. Major oil companies such as Shell, Agip, Amerada Hess, Chevron, Conoco, Elf, and Exxon participated in the project as co-sponsors drawing on knowledge flows from Petrobras. In some instances such unidirectional flows from Petrobras took the form of specific technology licensing arrangements or projects to transfer design and S&T knowledge to partners. For example, in 1998, the company established a collaboration for transferring instrumented pig technologies to a local supply company, Pipeway.

The diversity of different partner organisations continued through this period, and as indicated above, Petrobras itself was increasingly the main source of knowledge in some forms of network arrangement, for instance, when the company led and executed joint industry projects that included major oil companies as co-sponsors. Another illustration of this striking change was the company's growing participation in technology exchanges with a widening range of major oil companies. For instance, it established collaboration in multiphase pumping systems with Shell, BP Amoco, and Statoil, in deep water drilling with BP Amoco and Statoil, in deep water completion with Shell and in offshore platforms with Shell, BP Amoco and Statoil.

Petrobras recognised that the division of labour in innovative activities had to be distributed across what the company described as its 'technological system' formed by universities, suppliers, engineering companies, research institutes and other oil companies (cf. Baratelli *et al*. 1998:2). Petrobras decided that, its main task and particularly of its R&D centre, CENPES, was to coordinate and lead these R&D efforts and not necessarily to develop internally all the different systems and components. This key role became one of managing the integration of sub-systems and underlying knowledge bases across an array of different offshore technologies and via a range of symmetric and asymmetric – both internally- and externally-driven – organisational arrangements. In symmetric arrangements, both Petrobras and its partners in networks performed specialised and complementary R&D activities and Petrobras oversaw and coordinated the projects. This was the case in cooperation projects to joint develop incremental or major innovations with suppliers or S&T organisations. In externally-driven asymmetric arrangements, Petrobras joined the innovative efforts led by another oil company or supplier firm in which key R&D activities were undertaken by the network partner. This happened for instance when Petrobras joined joint industry projects led and executed by other organisations. Finally, a new form that was developed during this last period, Petrobras was increasingly involved in internally-driven asymmetric arrangements in which Petrobras itself was the leading performer of R&D activities within a given network arrangement, for instance, when Petrobras led joint industry projects and invited other oil companies to join in.

5. Conclusions

This study contributes to understanding about learning/innovation systems in several ways. Most of these centre specifically on the development of the knowledge network component – the backbone of learning/innovation systems, the development of which is still poorly understood (Edquist 1997, Malerba 2002). This is particularly the case in late industrialising countries because most knowledge network studies have focused on networks in developed countries and, as noted in Section 1, most of the studies in developing countries have observed the absence or weakness of interactions among organisations, not their emergence and development over the long term.

Our paper has moved beyond these limitations by identifying the positive development of the knowledge network of a specific organisation in a late industrialising context, providing evidence about its long term development over more than thirty years. It has shown that there were continuous shifts in the properties of the Petrobras-centred knowledge network over this period.[4]

- Perhaps the key feature underpinning these shifts was a sequence of changes in the decision-making process associated with the company's use of knowledge networks. This became increasingly purposeful or 'intentional'. It started as a purely passive approach in which knowledge accumulation within networks was more or less a by-product from the acquisition of goods and services, and it then moved through a succession of management perspectives that focused explicitly on using networks to achieve objectives about knowledge accumulation (learning), subsequently about innovation and finally, to mobilise complementary capabilities distributed outside the firm's boundaries. Stemming from this, other properties of the company's knowledge network became increasingly complex and diverse, with growing complementarity in knowledge production between the actors.
- Technological accumulation activities within knowledge networks became consistently more complex, evolving from simple assimilative activities to those involving different kinds of knowledge accumulation associated with innovation and the accumulation of strategic corporate assets.
- The directions of knowledge flows became more diverse, and the content of flows more complex and comprehensive.
- The sources of knowledge within the network became increasingly diverse, shifting from a concentration largely on supplier firms to encompass those plus a host of academic and other public technology institutes and a wide array of leading competitors in the industry. This also included the prominent role that the company

itself assumed as source of knowledge in its networks.

- The division of labour in knowledge production between the company and its partners became more diverse, balanced and complementary – later coming to encompass a combination of symmetric and asymmetric arrangements for driving and coordinating collaborative knowledge production across a range of technologies with differing strategic significance for the company.

But the contribution of the paper goes beyond these descriptive insights, interesting as they are, to issues about methodology – relating to historical analysis and conceptual development.

First, analyses of processes occurring over time are obviously centrally important for understanding the development of learning/innovation systems in late industrialising economies (Bell, 2006). Consequently, since there are numerous problems about real-time longitudinal studies (not the least being the absence of funding to carry them out), retrospective historical analysis has a large role to play. In this study we have demonstrated that a combination of methods, carefully applied, can be used to reconstruct key features of knowledge networks over a long period of time – with, we believe, considerable reliability in the data generated.[5]

Second, however, the issue of concept development and operationalisation is perhaps even more important. We have outlined and applied a systematic framework of network properties and the different forms these can take. This provides an essential basis without which three kinds of analysis are impossible. The first, the only one undertaken in this paper, is orderly (rather than disorderly, inconsistent and idiosyncratic) description. The second is comparison across different experiences – impossible without a common framework within which to order observations. The third is analytical explanation, ultimately the most important. This has been an important element in the overall study from which the material in this paper has been extracted (Dantas 2006), and it merits a brief concluding comment.

As noted earlier in Section 1, our focus on knowledge networks has addressed only one of several key components of learning/innovation systems, and the relationships between these 'building blocks' are key elements in explaining the overall evolution of such systems. This is evidently so in the larger study lying behind this paper and within which the systematic typology of network properties has been essential in developing an explanatory analysis. This has two steps.

First, interactions between the firm's internal capabilities and it knowledge network were critically important. As outline in Dantas and Bell (2006), the company's knowledge network played a key role as a set of channels and mechanisms that massively enhanced the internal accumulation of capabilities. But the existence of different levels of capabilities at particular times played key roles in enabling the company to enter and exploit particular types of network – they acted as 'entry tickets' without which Petrobras could not have pursued the cumulative development of the network in the way we have outlined.

Second, those capability-network interactions were in turn shaped by other components of the overall learning/innovation system: the technology with which the system was concerned and the institutional context within which it is embedded. The nature of the technologies required for increasingly deep-water production in Brazilian waters simply could not have been drawn from an existing shelf of techniques, methods and equipment. Beyond a certain point the further development of the industry depended on innovation by someone. Then, the fact that it was Petrobras that came to play a leading role in that innovation was shaped by aspects of the wider institutional regime within which the company was embedded – in one form consisting of the developmental role of the government and of Petrobras during the key phases of the industry's development up to the late 1990s, and then in another form in the subsequent period of liberalisation.

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