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Latecomer firms and the emergence and development of knowledge networks: The case of Petrobras in Brazil

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ABSTRACT

This paper addresses the emergence and development of firm-centred knowledge networks within learning and innovation systems in late-industrialising countries. A key contribution of the paper is conceptual and methodological: the development of an original typology of knowledge network properties to trace out changes in the form of networks as they evolve over time. A second contribution consists in providing an example of the application of the typology by examining the emergence and development of a firm-centred knowledge network in the case of Petrobras, the Brazilian oil company over more than 30 years between the late 1960s and the early 2000s. This demonstrates that the properties of Petrobras' knowledge networks continuously evolved through a succession of stages towards (i) increasing intentionality in the management decision-making underlying network development, (ii) growing complexity and diversity in selected cognitive characteristics, and (iii) greater complementarity in the division of innovative labour between Petrobras and its network partners. These original results from applying the typology, in conjunction with retrospective historical methods, illustrate only one aspect of its potential value in the analysis of knowledge networks in late-industrialising economies: tracking out organisational evolution over long periods of time. Others include the comparative examination of network differences across different circumstances and the analysis of relationships between changes/differences in network properties and other characteristics of learning/innovation systems and their contexts.

1. Introduction

The analysis of technological learning in latecomer economies has shifted over recent years from its focus on capability building in individual firms in the 1980s and 1990s to examine the development of learning and innovation systems. 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 and knowledge bases 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 concentrate on the second block (knowledge networks) because this seems to be the system component that has been most neglected in studies of innovation systems in latecomer economies. But this focus abstracts from important interactions among all the main system components, some of them helping to explain the way knowledge links and networks develop. Consequently, we will re-connect our knowledge network study with aspects of its wider system framework at two points: in outlining the empirical context of the case study in Section 2 and again at the end of the paper.

The importance of understanding the long-term dynamics of knowledge-centred networks in late-industrialising economies became increasingly clear as several studies in even quite mature economies highlighted the existence of constellations of firms that were not embedded in 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 not to demonstrate one of the necessary properties of innovation systems – 'system-ness'. There have been numerous studies of various aspects of that situation but they have been limited in two main ways.

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[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).

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First, most have involved static analyses of the current characteristics of innovation systems, and only a few have addressed issues about whether and how key aspects of networks emerge and change over time as part of a development process. Among the latter, only a very small number have shown some 'positive' development of network 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, only a body of largely static and generally 'negative' observations has been accumulated so far. This provides a very limited basis for comparative analysis of the development of differing and changing system characteristics.

But a second limitation is probably more important: the conceptual framework for the analysis of changing knowledge networks remains weak. This contrasts with research on the accumulation of innovative capability in individual enterprises, where well-structured 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 similarly structured conceptualizations of difference and change in the properties of knowledge networks in late-industrialising contexts, a limitation that further precludes systematic comparative analysis.

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 the only characterisation of how these may change over time is in terms of their frequency – increasing from "some" to "extensive" (p. 254). Bell and Albu (1999) take things a bit further in outlining a framework for assessing the evolution of cluster knowledge systems 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 may shift as system structures evolve from forms that are "unstructured, passive and closed" towards those that are "structured, active and open". However, such outlines are conjectural and have not been applied in any empirical analyses of the evolution of innovation systems in developing countries.

This paper aims to make two contributions to addressing these limitations. It outlines an original taxonomy of the properties of knowledge networks that are identified as particularly important in understanding the dynamics of network development in late-industrialising contexts. It then provides an illustrative example of the application of the taxonomy in examining the initial emergence and development of a firm-centred knowledge network concerned with offshore oil technologies and the Brazilian company, Petrobras. The study presents a 'positive' case study of the extensive emergence and development of the company's knowledge networks over more than 30 years between the late 1960s and the early 2000s. The analysis goes beyond the assessment of one-to-one linkages. By consolidating observations about commonalities and differences in the characteristics of individual linkages across different technologies at different times, it draws a composite synthesis of the properties of the company's network in offshore technologies as a whole and how those properties changed over time.

The paper is organised as follows. Section 2 presents the context of the firm-level study, noting briefly some of the factors that influence the path of network development. Section 3 introduces the taxonomic framework and Section 4 outlines other aspects of research design and method. Section 5 presents the empirical evidence and Section 6 provides a concluding discussion.

2. Petrobras and its 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 oil 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 2700 bbl per day (Petrobras, 1994: pp. 13 and 14) and in 1955, the proportion of national production in total domestic consumption was 7.34% (Dantas, 1999: p. 84).

The initial emphasis of the company's investments 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,[2] sinking to as low as 24% in 1971 (Dias and Quaglino, 1993: p. 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: p. 164).

As existing onshore reserves declined, the company increased its exploratory efforts on the offshore continental shelf which led to the eventual discovery of the Guaricema field in 1968, and then several other fields off the Brazilian Northeast coast. It increased the share of its investment expenditure allocated to exploration and production from 24% in 1971 to around 83% in 1985 (Dias and Quaglino, 1993: p. 135). In 1974 major oil reserves were discovered in the Campos Basin off the coast of Rio de Janeiro state, and proven Brazilian oil reserves climbed to 1.3 billion bbl by 1980 (Furtado, 1995: pp. 166 and 122). At the same time, high oil prices and difficulties in the Brazilian balance of trade following the oil crisis in 1973 had created strong pressures to expand national production by accelerating offshore development. Petrobras' production capacity increased from 180 000 to 563 000 bbl per day between 1980 and 1985 (Furtado, 1995: p. 166), and offshore production overtook onshore production in 1982 (Freitas, 1999: p. 82). With the intensification of offshore activities in the Campos Basin during the late 1970s and 1980s, the share of domestic production in total consumption reached the 50% threshold by 1985. By then, in 1984/1985, Petrobras had discovered giant deep water oil fields in the Campos basin, with the majority of oil resources in deep waters (>400 m) and some fields located at depths of up to 2100 m.

Through the late 1980s and early 1990s, Petrobras was responsible for the rapid development of these deep water resources, but its monopoly ended in 1997 and the major international oil companies started operating in Brazil. In the early 2000s, Petrobras was ranked overall as the 12th among the world's 50 largest oil companies, (Petroleum Intelligence Weekly, 2001). However, with about 60% of its total production of 1.35 million bbl per day in 2001 coming from deep and ultra-deep water fields, Petrobras was the world leader in deep water production.

During the whole period of offshore industry development, several factors shaped the technological development of the company and its participation in knowledge networks. One group of these was associated with technology. First, as water depths increased after the discovery of the Campos Basin fields in 1974, Petrobras came to face growing demands for globally novel technologies and

[2] 'Upstream' activities in the oil industry are usually recognised as those concerned with exploration and the production of crude oil before it is refined.

Table 1
Selected properties of knowledge networks.

Properties	Varying forms of properties			
	1	2	3	4
i) Intentionality underlying the development of the network	Passively engaged in the acquisition of knowledge via networks largely as a by-product of activities with other objectives	Actively centred on using networks to achieve learning objectives	Actively centred on using networks to achieve innovation objectives	Strategically centred on using networks as 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.

this created strong incentives for the company to widen its networks. But it also increasingly found that the technologies needed to exploit those deep water resources were not available in the international market and had to be created – partly because, after the collapse of oil prices in 1986, there was very limited investment in deep water projects in other offshore provinces around the world. Second, the development of offshore technologies was characterised by rapidly growing complexity – as reflected in the needs for: (a) technological advances to meet the performance requirements of extreme temperatures, pressures, structural stress and remoteness in deep water conditions; (b) the integration of a multitude of technical systems in offshore exploration and production systems (e.g. offshore structures, extraction and lifting systems, processing systems, drilling systems, storage and offloading systems, and so forth); and (c) the integration of diverse knowledge bases (e.g. naval architecture, ocean engineering, geosciences, ICTs, material technologies, chemical engineering, electrical engineering and so forth). This combination of technology-related issues called for extensive collaborative efforts on the part of Petrobras and other actors.

This was reinforced by a second group of factors associated with Petrobras' institutional role in Brazil – essentially a combination of a monopoly oil producer for a large part of the period and a pro-active, public sector 'development agency'.[3] The Brazilian debt crisis in the early 1980s added urgency to the need to increase oil production in the deep water basins, and it became clear that, because of its institutional role, Petrobras could not wait for the major oil companies and international suppliers to develop the necessary technologies in their own time. This led the company to make considerable efforts to catch up technologically, and subsequently to forge ahead with the *development* of deep water technologies. This inevitably called not only for a dense network of collaborations, but also for change in the nature of collaboration as catching up turned towards forging ahead.

A third group of factors was associated with the company's internal technological capabilities that shifted dramatically from those of an imitative technology-user to those of a leading player at the international innovation frontier. By the early mid 1990s, Petrobras was playing a leading role in the international industry in creating and applying totally novel technologies as it repeatedly broke world records in production and drilling water depths. As we have argued elsewhere (Dantas, 2006; Dantas and Bell, 2006), this continuous accumulation and transformation of capabilities enabled the company to change the ways it used knowledge networks, and also helped to change the form of those networks.

3. The emergence and development of knowledge networks: a framework for analysis

Based on Orsenigo et al. (2001: pp. 485 and 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 emergence and development of 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 the networks over time.

This paper focuses on their cognitive properties. To do so, it applies a conceptual framework covering key aspects of the evolution of firm-centred knowledge networks in late-industrialising economies. This draws on several areas of literature. Some of these are specifically concerned with knowledge networks in the context of innovation systems – their general characteristics (e.g. Breschi

[3] In these respects Petrobras was comparable to Embraer, the similarly technologically active Brazilian aircraft producer.

and Malerba, 1997; Carlsson and Stankiewicz, 1995; Gelsing, 1992; Niosi et al., 1993; Orsenigo et al., 2001; Saviotti, 1997), their dynamics (e.g. Malerba, 2002, 2004; McKelvey, 1997; McKelvey and Orsenigo, 2001), and their particular characteristics in late-industrialising economies (e.g. Bell and Albu, 1999; Viotti, 2002). Other contributing literature has addressed aspects of knowledge networks with a less direct connection to innovation systems – their boundaries, dynamics and different types (e.g. Coombs et al., 1996; Hagedoorn and Schakenraad, 1990; Håkansson, 1987; Håkansson and Lundgren, 1995; Powell et al., 1996; Mytelka, 2001a,b). We also draw on more specific illumination of particular issues – about the dynamics of overall networks in addition to individual one-to-one linkages (e.g. Mytelka, 2001a,b; Hagedoorn and Duysters, 2002), about the content, complexity and direction of knowledge flows (e.g. Machlup, 1962; Gibbons and Johnston, 1974; Vicenti, 1990; Senker and Faulkner, 1996; Nooteboom, 1999; Ariffin, 2000), and about the division of knowledge labour between actors, the purposiveness of actors, and other actor-centred aspects (e.g. Bell, 1984; Axelsson, 1995; Britto, 1998; Brusoni et al., 2001; Powell and Grodal, 2005). Building on the insights of these different literatures, and more generally on the literature about innovation systems in developing countries, our analysis of network emergence and development concentrates on the following five selected properties of knowledge networks in late-industrialising economies (see Table 1):

(i) the *intentionality in decision-making* underpinning the emergence and development of the network: concerned with the extent to which networks are explicitly and deliberately developed to support technological accumulation;
(ii) the *nature of technological accumulation activities* carried out within the collaborative network: concerned with the forms of technology involved (e.g. embodied in goods and services or disembodied knowledge about advanced technologies), and with the difference between 'passive' technology using and 'active' technology creating;
(iii) the *content and direction of knowledge flows* contributing to further technological accumulation: concerned with their complexity and the diversity of directions[4];
(iv) the *sources of knowledge flows*: concerned primarily with their diversity;
(v) the *division of labour in knowledge production* between the core nodal player and its partners: concerned with the nature and complementarity of the knowledge production roles of actors in the network.

Each of these cognitive properties can assume different forms that may (or may not) change through time or differ across contexts. These different forms are classified here into four categories for each of the cognitive properties, and these are aligned in the four columns under (1)–(4) in Table 1.[5] 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.[6]

At one extreme (Column 1) the combination of forms is summarised as a '*passive learning network*', involving (i) passive intentionality in decision-making underpinning the emergence and development of the network, (ii) an emphasis on using networks to accumulate technology only in the forms of knowledge embodied in goods, services and associated operational know-how, (iii) primarily unidirectional, but also bidirectional, flows of operational knowledge,[7] (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 4), the combination of forms is summarised as a '*strategic innovation network*', characterised by (i) strategic intentions to use networks as a means 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 located 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: '*active learning networks*' (Column 2) and '*innovation networks*' (Column 3). However, our indication of the possibility of knowledge networks evolving between Levels 1 and 4 involves no presumptions about optimality or linearity. The categories in the taxonomy are generated out of the specific experience of Petrobras, but there is no archetypical ideal network for all firms or industries, and evolution is not presumed to follow any generally applicable linear path through Table 1.

4. Research design and method

The use of a single case study centred on Petrobras stemmed from three considerations. First, in order to pursue the exploratory application of the taxonomy, it was important to obtain observations across as wide a range of the taxonomy cells as possible, while also limiting the variability in other factors. That pointed towards the selection of a small number of case study firms, or perhaps just one, which would demonstrate considerable diversity in observable network characteristics. Second, in order to link that exploration to understanding how network forms *changed* over time, it was important to ensure that the selected firm(s) had experienced significant paths of positive network development over reasonable periods of time – consequently contrasting with most previous studies in late-industrialising contexts that had focused on the weakness of knowledge networks. Previous research (e.g. Dantas, 1999; Freitas, 1999) indicated that Petrobras would meet these requirements, and initial work with the company highlighted the third set of considerations – operational practicalities. The need to analyse network development over a reasonably long period of time and to collect data from multiple sources within and outside the firm 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.

[4] In principle, the content and the direction of knowledge flows could each be treated as a distinct network property. In this case, however, they were closely correlated and for purposes of simplification are combined.

[5] As noted later, this differentiation of the cognitive properties was not fully constructed a priori. Basic elements of difference were derived from the literature, but the classification was refined during the analysis of data. Consequently the details of the taxonomy 'emerged' from and were 'grounded' in the empirical observation.

[6] 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.

[7] Fragmentary descriptions in the literature suggests that flows of operational knowledge at early stages of network development in industrialising economies are likely to be predominantly unidirectional – from suppliers to users. The inclusion of bidirectional flows in the first category here reflects the grounding of the conceptual framework in Petrobras' specific experience. Early in the company's expansion of offshore production, suppliers were developing many of the technologies for the unusual conditions of the Brazilian fields, and feedback flows of knowledge from Petrobras about its operational experience were important – see Section 5.1.

Table 2
The technological scope of the case study.

Timing of relevance of technologies in the company's portfolio	The sample of technologies covered	Illustrative examples of partners
Technologies relevant in the complete period analysed in the study	*Semi-submersible platforms* (Floating structures hosting production or drilling facilities whose stability is enhanced by a substantial fraction of the structure being kept below the water surface)	Sedco-Hamilton; Gotaverken Arendal; Verolme Ishibras; Marítima; Tenenge; Ultratec; Fels; Jurong; COPPE; Chalmers University; University of Reading; USP
	Wet Christmas trees (System of valves and other instruments installed at the well-head of a producing well located on the seabed to control oil flow)	Vetco; Hughes; Cameron; FMC; CBV; ABB; Kvaener; COPPE; PUC-Rio
	Flexible flowlines and risers ('Pipes' carrying oil/gas to the surface and injection materials, etc. to the well)	Coflexip; Veritec; Brasflex; Flexibras; Wellstream; Marine; COPPE; Foundation for Scientific and Industrial Research
	Umbilicals (Systems for carrying data signals, power, etc. between well and platform)	Oceaneering Multiflex; Atry-Nylox; Pirelli; MFX; COPPE
	Basin analysis and modelling (Exploration method that analyses the geological evolution of sedimentary basins and their potential hydrocarbon content)	IBM; French Institute of Petroleum; Integrated Exploration Systems; Geologica; University of Ouro Preto; University of Texas at Austin; COPPE; PUC-Rio; Lamont Dohert Earth Observatory; University of Newcastle upon Tyne; University of Indiana
	Well technologies and drilling (Technologies for drilling wells and managing, controlling and monitoring their characteristics and operation)	Schlumberger; Maurer Engineering; Smedvig; Marathon Oil; Air Drilling Services; Wellmasters; Drillquip; University of Oklahoma; PUC-Rio; Institute for Technological Research (IPT); COPPE; UNICAMP; BP; Mobil; Amerada Hess
	Seismic-stratigraphy (Exploration method through which the characteristics of sedimentary rocks are observed from seismic data)	University of Ouro Preto; University of Texas; Landmark, GeoQuest, Schlumberger
	Analysis of turbidite formations (Methods of analysis of geological formations that have been formed as a result of fast and sediment-loaded underwater currents)	University of Parma; UERJ; University of Texas; University of Illinois; UFRJ; UENF; Schlumberger
	Control systems (Devices to manage and control subsea equipment)	Brasnor; FMC; Cameron
Technologies that became relevant in last three time periods (from mid 1980s)	*Instrumented pigs* (Devices for surveying, testing and clearing pipelines internally)	PipeWay; Transcontrol; Tuboscope; PUC-Rio; USP
	Multiphase pumping systems (System to pump and transfer complex multiphase effluents (fluids, gases and solid) from a producing well to a remote location such as a platform)	Weir Pumps; Pompes Guinard; Bornemann; Multiphase Systems; French Institute of Petroleum; COPPE; Westinghouse; Leistritz, Imperial College; Fluenta; Texaco; Shell; Exxon; Amerada Hess; Conoco; Chevron, BP
	Remotely operated vehicles (Unmanned mini-submarines used in offshore operations for inspection, installations, operations, etc.)	Consub; PUC-Rio; COPPE
Technologies that ceased to be relevant for the company in the first or second periods	*Fixed platforms* (*relevant until early 1990s*) (Steel or concrete structures equipped with production facilities that are fixed to the seabed, rather than floating)	Hudson Engineering Co.; PMB Systems Engineering; CJB; Earl and Wright; Brown and Root; Interconsult
	Atmospheric well-head cellars (*relevant until mid 1980s*) (Underwater production system encapsulating subsea well-head and Christmas trees working in atmospheric condition)	Lockheed

Investigation of the network was based on the integration of data about a sample of 14 different offshore technologies in order to provide reasonably representative coverage 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.[8]

[8] However, we frequently refer to the company's knowledge networks (in the plural) as a reminder that we are dealing with a constructed composite rather than a singular and homogeneous entity.

The main body of data was collected through 114 semi-structured interviews with managers, engineers and R&D personnel in the focal company and its partners (e.g. suppliers, S&T organisations) who had been involved in collaborations with the company in the selected technologies. These semi-structured interviews provided descriptive information about the history of technology-related collaborations in each of the 14 technology areas and different time periods – questions about the latter being open-ended and depending on the scope of knowledge of the respondents. For each technology the interviews covered issues about the objectives of the collaborations, the kind of technological activities involved, the kind of knowledge each partner provided to and drew from the collaboration, the main partners and how tasks were divided among them, as well as the ways in which these features changed and differed. Column B in Appendix A Table A1 lists the questions asked to interviewees in these areas, and examples of the resulting information are provided in Column C.

In addition, information was collected through informal meetings with key individuals and from documentary sources. The narratives about the history of knowledge network development in selected technologies collected through interviews was complemented by a number of company technical reports focusing on collaborative technological developments, as well as technical articles published by Petrobras and collaborators in the relevant technologies.

The analysis of the data fell into three stages. First, a set of four time periods was identified. This periodisation was exogenous to the basic taxonomy, reflecting key 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, as detailed in Column D of Appendix A Table A1, a number of indicators corresponding to the different observed forms of network properties were identified, and a set of decision rules (Column E in Appendix A Table A1) was developed for classifying the indicators into different 'levels' of network property development – corresponding to the different entries across the columns in Table 1 earlier. Based on these procedures running from interview questions to classification rules in Appendix A Table A1, the analysis first generated descriptive data displays for each of the network properties in Table 1 – as illustrated selectively in Column C of Appendix A Table A1. That descriptive information was collapsed to the Column D indicators associated with each of the five network properties for each of the 14 technology areas and four time periods – i.e. 280 sets of descriptive indicators. These were used to classify differences in each of the network properties in terms of the Levels 1–4 shown in Table 1.

Then third, the data displays were analysed using several approaches. Commonalities and differences in the 'levels' of network properties associated with technologies and time periods were identified. This led to the identification of a frequent intra-period heterogeneity. While there were very often 'dominant' levels in technology/time period cells (as evident for the majority of the collaborations), there also often emerged 'higher' levels in a few technology areas towards the end of the period. This led to an additional distinction between 'dominant' and 'emerging' forms of the network properties in each technology/period. Further data displays moved the analysis from individual technologies to aggregate, cross-technology syntheses of dominant and emerging forms of properties for periods. In principle these were based on the forms demonstrated by the majority of the technologies, but in practice there was usually much greater consistency within the periods. The data were thus reorganised into a structured chronology that we outline in the next section.

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

Petrobras massively transformed its offshore technology networks between the late 1960s and the early 2000s moving right across Table 1 from a *passive learning network* to a *strategic innovation network*. We examine that transformation through Sections 5.1–5.4 with respect to each of the four periods, noting for each period except the last the distinction between (a) the form of property that was '*dominant*' and pervasive across different technologies and (b) new forms that were '*emerging*' in a few selected areas of technology, usually towards the end of a period. These successive developments are summarised in Table 3.

5.1. The late 1960s–1984: from a passive towards an active learning network

With the beginning of Petrobras' offshore operations, an embryonic knowledge network concerned with its offshore technologies started to take shape around the company. The dominant pattern that was consolidated during this period consisted of what is summarised in Table 3 as a passive learning network. It was characterised by the following forms of the various network properties.

With respect to 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. Any learning outcomes and flows of knowledge that were acquired were passive by-products of the transfer of these goods and services.

The firm's technology accumulation activities associated with these 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 that had been converted to undertake 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. In such ways Petrobras continuously interacted with supply firms in order to obtain offshore technologies and regularly 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 organisations 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 complemented 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. This pattern became evident, 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 installation and operation. This included information about operational problems that needed to

Table 3
The development of Petrobras' knowledge network.

Network properties	Late 1960s–1984		1985–1991		1992–1996		1997–early 2000s
	Dominant	Emerging	Dominant	Emerging	Dominant	Emerging	Consolidating
i) Intentionality underlying the development of network	Passive	Active for learning	Active for learning	Active for innovation	Active for innovation	Strategic	Strategic
ii) Technological accumulation activities with which the network is concerned	Acquisition and assimilation of goods, services and operational know-how	Learning and absorption of design and S&T knowledge underpinning technologies/adaptations	Learning and absorption of design and S&T knowledge underpinning technologies. Hybrid innovation for learning	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. Transfers of technology to partners. Exchanges of technology
iii) Content and directions of knowledge flows enhancing capability accumulation	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 firm	Reverse unidirectional flows of design and S&T knowledge	Combination of bidirectional, unidirectional and reverse unidirectional flows of design and S&T knowledge
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) Division of labour in knowledge production	Asymmetric knowledge production with key knowledge-producing activities external in partners	Increasing participation in knowledge production via mostly asymmetric arrangements	Increasing participation in knowledge production via mostly asymmetric arrangements	Symmetric specialised knowledge production between nodal player and partners	Symmetric specialised knowledge production between nodal player and partners, but also asymmetric external	Asymmetric knowledge production with key knowledge-producing activities internal in the nodal player	Symmetric 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.

be addressed through re-design of the equipment, as well as the identification of further requirements to adapt the equipment for 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 developed these, and the first use of the technology in the world was in Petrobras' Garoupa-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 network property associated with more active learning activities 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, technological and scientific 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.

5.2. 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 developed much more active and pervasive intentions to use knowledge networks to achieve learning-related objectives, not merely to acquire knowledge passively as a by-product from purchasing goods and services plus associated operating know-how. Petrobras decided to enter knowledge networking at this stage to learn about and internalise the design, and S&T knowledge through the collaborations in order to pursue independent knowledge-producing activities related to its own R&D, in the future. Thus, one of Petrobras' main emerging aims was to use knowledge networks to help reach a greater degree of self-sufficiency in technological development (Petrobras, 1998: p. 29).

Consequently the focus on technological accumulation activities within the networks shifted pervasively 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 Alberto Luiz Coimbra Institute (COPPE) at the Federal University of Rio de Janeiro 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 in order to carry out design work. Thus, in contrast to the previous phase where the emphasis was on the flows of operational knowledge, the content of knowledge flows now, involved more complex design and scientific knowledge, though 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. These 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 about 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 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 overall character of knowledge networks took a hybrid 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, Consub (a Brazilian supply company), COPPE and PUC-Rio in remotely operated vehicles. These kinds of network 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 to act 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.

5.3. 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 scientific and technological understanding about offshore technologies in the previous period, the company realised that the earlier technological self-sufficiency objective was unsustainable – it was not feasible to hold in-house all the S&T knowledge bases relevant to exploration and production technologies, and 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 synergistic collaborations with partners both in Brazil and abroad" (Petrobras, 1998: pp. 29 and 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 the networked innovative efforts of the company also included complementary participation in collaborations that were coordinated by other organisations and involved unidirectional flows of S&T knowledge from the main executor of the project to Petrobras – as, for instance, when Petrobras engaged in joint industry projects led by the Imperial College, the UK National Engineering Laboratory and Texaco, respectively, to monitor the development of different concepts of subsea multiphase flow meters.

These innovation-centred interactions were frequently characterised by an increasingly symmetric division of labour in knowledge production between Petrobras and its partners. In the collaborations for joint incremental innovation and joint development of major innovations and novel concepts, Petrobras coordinated the projects and the company and each partner carried out specialised and complementary R&D activities. For instance, in a collaboration with PUC-Rio to develop an instrumented pig, Petrobras developed the magnetic sensors and mechanical design, and PUC-Rio developed the electronics, the electrical components, and the software. But these symmetrical collaborations were also complemented by asymmetric arrangements, mainly joint industry projects, in which key R&D activities were externally located in network partners. Petrobras participated as a co-sponsor of the R&D efforts that were coordinated and executed by leading organisations in offshore technologies and it 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 from 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. Petrobras increasingly saw knowledge networks 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 a 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.

5.4. 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 an array of knowledge bases that were attractive to other companies. Conversely, Petrobras also 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 flows 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 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: p. 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 organisational arrangements – both internally- and externally-driven. 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.

6. Concluding discussion

This study has not been designed to provide generalisable empirical observations or to offer immediate guidelines for management or policy. Instead, it has sought to contribute a step to greater understanding about the emergence and development of knowledge networks, a key component of learning/innovation systems that is still poorly understood (Edquist, 1997; Malerba, 2002), especially in late-industrialising countries. That step has involved exploring the application of the original taxonomy outlined in Section 3 via a case study of a single firm that was expected in advance to demonstrate considerable diversity in the observable characteristics of its knowledge networks, especially as a consequence of their change over time. This has provided a number of insights. We discuss three of these here: (i) the significance and nature of 'qualitative' change in network development; (ii) the contingent nature of the process of network change; and (iii) the demonstration of feasible research method in the absence of relevant secondary data.

6.1. The significance of 'qualitative' change in network development

Discussion of the weakness of knowledge links and networks in late-industrialising countries tends to be couched in terms of quantity – there are '*not enough*' links or the density of network structures is '*too low*', usually relative to apparent benchmark comparators in more technologically advanced economies. Our study, however, has adopted a different focus by concentrating on various qualitative characteristics of networks that have been identified as important in previous studies. We have shown that there were considerable shifts in these qualitative properties of the Petrobras-centred knowledge network.[9]

- 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.

[9] 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 all technologies at particular times – although, as we stress below, there were surprisingly consistent 'dominant' patterns.

- 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.

These insights help to bridge across a wide gap in the literature between two kinds of observation about knowledge-centred linkages: (i) the types of non-interactive agglomeration of firms and other organisations in late-industrialising economies, described for instance by Lastres et al. (2003) as "productive arrangements" and (ii) the kinds of organisational structure described by Chesborough (2003) as modes of "open innovation" at the international frontiers of technology in contemporary advanced economies.

6.2. The contingent nature of the process of network change

It is important to recall the set of contextual conditions outlined in Section 2. These constitute a compendium of potentially important factors in explaining the path of qualitative change summarised above. Some were technology-related – associated with the demand for novel technologies to exploit increasingly deep water resources, and also with various kinds of 'complexity' of the technology involved in offshore exploration and production. Some were institutional – associated with the particular position of Petrobras in the Brazilian industrial and political system; and some were concerned with the internal technological and managerial capabilities of Petrobras itself.

The scope of this paper cannot encompass more detailed exploration of these explanatory factors.[10] But further questions about the apparent significance of such contingent conditions are raised by an aspect of our results that seems surprising: the consistency of the '*dominant*' forms of network property across technologies within individual time periods – as summarised in Table 3.[11] It is important here to recall that: (i) the time periods were defined in terms of key changes in the industry's development and independently of the pattern of networking behaviour by Petrobras and (ii) we reviewed networking behaviour across 14 different areas of technology – though, as shown in Table 2, not all of these were involved in all time periods. We interpret intra-period consistency in these circumstances as suggesting the existence to two strong interacting forces. On the one hand, aspects of external technological, industrial, economic and political conditions that differentiated the periods must have generated strong pressures on Petrobras to follow particular approaches in its technological behaviour. On the other, strong intra-corporate integrating forces must have operated to shape common approaches across the different areas of technology in the company.

6.3. The demonstration of feasible research method

Our case study illustrates the potential value of the conceptual framework underlying the empirical analysis in the paper – the systematic taxonomy of network properties and the different forms these can take. The concepts that were drawn from previous research and integrated in this taxonomy proved useful and illuminating in analysing the responses to what were very open-ended interview questions about knowledge-centred links in Petrobras. This should provide an adaptable basis for subsequent work in this area.

Beyond that, the study also illuminates the feasibility of analysing change in these network characteristics over relatively long periods of time. This is obviously important for understanding the *emergence and development* of learning/innovation systems in industrialising economies (Bell, 2006), and it has been demonstrated already in studies of multi-decade transitions in the technological capabilities of firms in late-industrialising economies (e.g. Kim, 1997 or Figueiredo, 2001). Here however, instead of focusing on change in the internal capabilities of firms during such transitions, we have sought to illuminate the dimension concerned with their external knowledge networks.

That is a demanding task because secondary data sources have limited relevance, especially in developing countries,[12] and original data acquisition from firms is necessary. It is therefore useful that we have demonstrated the feasibility of using a combination of methods to reconstruct key features of the long-term development of knowledge networks over more than 30 years – with, we believe, considerable reliability in the data generated. However, we would be cautious about recommending the same kind of design for future research – partly because of the resource cost involved in covering such a wide array of technologies over such a long period of time, and partly because designs involving multiple firms and the possibility of comparing across different circumstances may now be more important in developing this area of understanding.

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[10] The influence of these interacting factors in explaining the path of network change has been explored in the overall study from which the material in this paper has been extracted (Dantas, 2006). Also, we have examined in another paper the more specific interaction between the firm's internal capabilities and its knowledge network (Dantas and Bell, 2006).

[11] We are grateful to one of the anonymous reviewers of an earlier version of this paper for reminding us about the improbability of this pattern.

[12] Methods based on even the limited information about qualitative aspects of knowledge links that can be derived from sources like patent or publication citation records are largely inapplicable in late industrialisation contexts because firms engage in patenting and academic publication only at relatively late stages of their technological development. Innovation survey data is also unhelpful because the data about collaboration is very limited, and in any case consistent data sets running through surveys over a significant number of years have not yet been built up in these countries.

Appendix A

Table A1
Linking the interview data to the conceptual framework and classification.

A Properties	B What was asked to the persons interviewed?	C Examples of interview response information used to classify the network property levels for each technology and time period	D Indicators of the form of each property leading to classification of level	E Decision rules used to classify interview responses (Column C) as indicators of taxonomic levels (Column D)
Intentionality underlying the development of the network	Can you describe the collaborations with external partners in technology X during time periods you know about? What were the objectives of the interactions with external partners in these collaborations? How did these change over time?	The objective of collaborations in *atmospheric well-head cellars* (late 1960s–1984) was to acquire, install and commission a new offshore system, a dry subsea production system, based on the use of atmospheric well-head cellars encapsulating subsea equipment and placed on the seafloor	No explicit intention to use collaborations for learning or innovating; only to acquire equipment and services (*Level 1*)	The network property '*Intentionality*' was classified as *Level 1* for a technology if responses indicated that (a) 'to acquire equipment and services' was the primary objective, but not (b) 'to learn about a technology', 'to develop new technologies' and 'to access complementary external capabilities'
		The objective of collaborations in *multiphase pumping systems* (1985–1991) was to acquire design knowledge in this emerging technology. The company wanted to use collaborations as a 'scouting' effort to learn about the technology and its potentialities, to learn about design and development of such a system and to explore the different technical concepts being pursued by suppliers, oil companies and research organisations	Intention to use collaborations to learn about a technology (*Level 2*)	'*Intentionality*' was classified as *Level 2* for a technology if responses indicated that (a) 'to learn about a technology' was the main objective and 'to acquire equipment and services' may also be present, but not (b) 'to develop new technologies' and 'to access complementary external capabilities'
		The objective of collaborations in *umbilicals* (1992–1996) was to joint develop new electro-hydraulic umbilicals for ultra-deep water fields being developed in the period (over 1700 m water depth)	Intention to use collaborations to develop novel equipment, methods, etc. (*Level 3*)	'*Intentionality*' was classified as *Level 3* for a technology if responses indicated that (a) 'to develop new technologies' was the main objective and 'to learn about a technology' and 'to acquire equipment and services' may also be present, but not (b) 'to access complementary external capabilities'
		The objective of collaborations in *well technologies and drilling* (1997–early 2000s) was to access relevant competencies wherever they were located outside the company's boundaries, all of which could not be kept in-house because of the growing complexity and pace of change of offshore technologies, and bring them together in specific R&D projects to address the technological demands of the company	Intention to use collaborations to access complementary capabilities located outside the firm (*Level 4*)	'*Intentionality*' was classified as *Level 4* for a technology if responses indicated that (a) 'to access complementary external capabilities' and 'to develop new technologies' were the main relevant objectives, and (b) 'to learn about a technology' or 'to acquire equipment and services' may also be present
Technological accumulation activities with which the network is concerned	With which activities were these collaborations in technology X concerned? Did these change over time? How?	The network in *well technologies and drilling* (late 1960s–1984) involved the acquisition of drilling and logging services from service supply companies. While the suppliers executed the services, Petrobras personnel observed their operations, monitored drilling activities in the field and obtained experience about the operational performance and bottlenecks in drilling operations, sub-systems and equipment	Acquisition of goods, services and operational know-how (*Level 1*)	The network property '*Technological accumulation activities*' were classified as *Level 1* if responses indicated that (a) 'acquisition of goods, services and operational know-how' occurred, but not (b) 'joint adaptations of technologies', 'absorption of design and scientific knowledge underpinning technologies', 'joint R&D', 'reverse transfer of technology to partners', and 'exchange of technology with partners'
		The network in *flexible lines and risers* (1985–1991) was concerned with absorbing mechanical principles, design criteria and procedures, analytical methods and tools for development and design of risers and lines. Activities included participating as observer in R&D consortia led by partners, sending personnel for training in and monitoring of suppliers' design activities, and training programmes in universities	Joint adaptations of technologies; absorption of design and scientific knowledge underpinning technologies (*Level 2*)	'*Technological accumulation activities*' were classified as *Level 2* if responses indicated that (a) 'absorption of design and scientific knowledge underpinning technologies' and/or 'joint adaptations of technologies' occurred, but not (b) 'joint R&D', 'reverse transfer of technology to partners', and 'exchange of technology with partners'

Table A1 (*Continued*)

A Properties	B What was asked to the persons interviewed?	C Examples of interview response information used to classify the network property levels for each technology and time period	D Indicators of the form of each property leading to classification of level	E Decision rules used to classify interview responses (Column C) as indicators of taxonomic levels (Column D)
		The network in *wet Christmas trees* (1992–1996) involved joint R&D with partners in several collaborations on, for instance, a horizontal guidelineless tree to be part of a subsea electrical submersible pump for 1109 m water depth, a tree for 1800 m water depth for the South Marlim field, changes in existing tree designs to standardise the interfaces of different tree concepts with other subsea equipment, and a novel concept of autonomous wireless deep water Christmas tree	Research, development and design of new technologies; acquisition of scientific and design knowledge in different technical solutions (*Level 3*)	'*Technological accumulation activities*' were classified as *Level 3* if responses indicated that (a) 'joint R&D' occurred, and the 'acquisition of scientific and design knowledge in different technical solutions' may also be present; but not (b) 'reverse transfer of technology to partners' or 'exchange of technology with partners' (see also note below)
		Petrobras' network in *well technologies and drilling* (1997–early 2000s) involved, for instance, joint R&D with partners on new wellbore stability simulators; the acquisition of knowledge from partners on a new concept of composite drilling riser; the reverse transfer of technology from Petrobras to other oil companies on reservoir assessment methods and drilling hydraulics; and exchanges of technologies on drilling procedures with light-weight fluids with another oil company	R&D and design of new technologies; acquisition of scientific and design knowledge in new technical solutions; reverse transfer of technology to partners; and exchange of technology with partners (*Level 4*)	'*Technological accumulation activities*' were classified as *Level 4* if responses indicated that 'reverse transfer of technology to partners' and/or 'exchange of technology with partners' occurred in addition to 'joint R&D' and (but not necessarily) 'acquisition of scientific and design knowledge in different technical solutions'
Content and directions of knowledge flows in networks	What kind of knowledge did you obtain from your partners in these collaborations? Did this change over time? How? What kind of knowledge did you provide to your partners? Did this change over time? How?	The directions and types of flows in the network in *wet Christmas trees* (late 1960s–1984) consisted of one-way flows from suppliers, followed by two-way flows of knowledge between Petrobras and suppliers. These were about operating know-how, equipment performance, technical bottlenecks (e.g. faulty valve functioning), and required improvements (e.g. systems linking the tree and flowlines)	Unidirectional or bidirectional flows of operational knowledge between network partners and focal firm (*Level 1*)	The '*Directions and type of knowledge flows*' was classified as *Level 1* if responses indicated that (a) 'unidirectional or bidirectional flows of operational knowledge' between network partners and Petrobras occurred, but not (b) 'unidirectional' or 'bidirectional' flows of design and scientific knowledge' or 'reverse unidirectional flows of design and scientific knowledge' from Petrobras to partners
		The directions and types of flows in Petrobras' network in *basin analysis and modelling* (1985–1991) were made up of one-way flows from partners to Petrobras on theoretical knowledge and modelling and simulation concepts involved in basin analysis and analysis of geological evolution, and scientific principles in structural geology and tectonics	Predominantly unidirectional flows of design and scientific knowledge from network partners to focal firm (*Level 2*)	The '*Directions and type of knowledge flows*' was classified as *Level 2* if responses indicated that (a) 'unidirectional flows of design and scientific knowledge' from network partners to Petrobras occurred, but not (b) 'bilateral flows of design and scientific knowledge' or 'reverse unidirectional flows of design and scientific knowledge' from Petrobras to partners
		The directions and types of flows in the network in *instrumented pigs* (1992–1996) included bidirectional flows between Petrobras and partners, in which Petrobras provided the partners with knowledge on magnetic sensors, mechanical and software designs for magnetic corrosion, geometric and ultrasonic corrosion inspection tools. The company drew from one partner knowledge on electro-electronics, instrumentation and software designs to be applied in inspection tools, and from another partner experimental data, models and ultrasonic sensor designs on ultrasonic inspection techniques	Bidirectional flows between focal firm and network partners of design and scientific knowledge; and unidirectional flows from partners to focal firm of design and scientific knowledge (*Level 3*)	The '*Directions and type of knowledge flows*' was classified as *Level 3* if responses indicated that (a) 'bilateral flows of design and scientific knowledge' occurred and 'unidirectional flows of design and scientific knowledge from partners to Petrobras' may also be present; but not (b) 'reverse unidirectional flows of design and scientific knowledge' from Petrobras to partners

Table A1 (*Continued*)

A Properties	B What was asked to the persons interviewed?	C Examples of interview response information used to classify the network property levels for each technology and time period	D Indicators of the form of each property leading to classification of level	E Decision rules used to classify interview responses (Column C) as indicators of taxonomic levels (Column D)
		The directions and types of flows in Petrobras' network in *multiphase pumping systems* (1997–early 2000s) included, for instance, reverse unidirectional flows of knowledge from Petrobras (and a partner) to other oil companies covering designs and test results of a concept of subsea motor-multiphase pump sub-system; bilateral flows between Petrobras and suppliers about electro-optic umbilicals and a subsea integration module; and unidirectional flows of design knowledge from research organisation on a different technical concept of multiphase flow meters	Bidirectional, unidirectional and reverse unidirectional flows from focal firm to partners of design and scientific knowledge (*Level 4*)	The '*Directions and type of knowledge flows*' was classified as *Level 4* if responses indicated that (a) 'reverse unidirectional flows of design and scientific knowledge' from Petrobras to partners occurred, and 'bilateral flows of design and scientific knowledge'; and (b) 'unidirectional flows from partners to Petrobras' may also be present
Sources of knowledge flows	Who were your collaborating partners in technology X over this period? Who were key knowledge-producing actors in the network? Did these features of collaboration change? How?	Petrobras' network in *fixed platforms* (early part of period late 1960s–1984, until 1977) included as sources of knowledge supply companies (e.g. Earl and Wright, Brown and Root, and Interconsult)	Suppliers as knowledge sources (*Level 1*)	The network property '*Sources of knowledge flows*' was classified as *Level 1* if responses indicated that (a) the main types of external sources of knowledge in the network were suppliers, and not (b) S&T organisations, oil companies or Petrobras itself
		Petrobras' network in *flexible flowlines and risers* (1985–1991) included as sources of knowledge supply companies (e.g. DNV, Coflexip), S&T organisations (e.g. University of Texas), and other oil companies (e.g. Shell)	Suppliers; S&T organisations; other oil companies as knowledge sources (*Level 2*)	The property '*Sources of knowledge flows*' was classified as *Level 2* if responses indicated that (a) besides suppliers, other types of external sources of knowledge (i.e. S&T organisations or oil companies) were present, but (b) Petrobras itself did not act as a source of design and scientific knowledge flows to partners in the network
		Petrobras' network in *umbilicals* (1992–1996) included as sources of knowledge suppliers (e.g. Oceaneering Multiflex, Wellstream, Atry-Nylox), S&T organisations (e.g. COPPE, USP), and Petrobras as a source of complex design and scientific knowledge to partners	Suppliers; S&T organisations; other oil companies; focal firm itself as knowledge sources (*Level 3*)	The property '*Sources of knowledge flows*' was classified as *Level 3* if responses indicated that (a) Petrobras itself also acted as source of design and scientific knowledge flows to partners in the network, (b) besides suppliers, other types of external sources of knowledge (i.e. S&T organisations or oil companies) were present, but (c) Petrobras did not act as source of reverse unidirectional knowledge flows to partners in the network
		Petrobras' network in *semi-submersible platforms* (1997–early 2000s) included as sources of knowledge engineering companies (e.g. Marítima, Tenenge), universities (e.g. COPPE, USP), other oil companies (e.g. Shell, BP, Statoil) and Petrobras itself as source of reverse unidirectional flows on semi-submersible design concept to other oil companies	Suppliers; S&T organisations; other oil companies; focal firm itself is an increasingly important source of complex knowledge to partners in network (*Level 4*)	The property '*Sources of knowledge flows*' was classified as *Level 4* if responses indicated that (a) Petrobras acted as a source of reverse unidirectional design and scientific knowledge flows to partners and (b) besides suppliers, other types of external sources of knowledge (i.e. S&T organisations or oil companies) were present
Division of labour in knowledge production between the focal firm and others	How were tasks divided among partners in the collaborations? Who did what? Did this change? How?	The division of labour in knowledge production in *flexible lines and risers* (late 1960s–1984) involved an arrangement in which research, development and design activities leading to the introduction of new flowlines and risers for deeper waters were the responsibility of the supplier, Coflexip. In the case of flexible risers, even the detailed design of the specific configuration of risers for specific production systems was carried out by the supplier. Petrobras' only contribution to the generation of new knowledge in this technology during this time period was through the operation of the equipment	Asymmetric arrangements (partners undertaking R&D and design, with the focal firm producing only knowledge associated with production and operation) (*Level 1*)	The property '*division of labour in knowledge production*' was classified as *Level 1* if responses indicated that (a) 'asymmetric external arrangements' were present, but not (b) the company undertaking design or R&D activities with assistance from partners, and either 'symmetric arrangements' or 'asymmetric internal arrangements'

Table A1 (*Continued*)

A Properties	B What was asked to the persons interviewed?	C Examples of interview response information used to classify the network property levels for each technology and time period	D Indicators of the form of each property leading to classification of level	E Decision rules used to classify interview responses (Column C) as indicators of taxonomic levels (Column D)
		The division of tasks in the network in *semi-submersible platforms* (1985–1991) involved partners executing the basic design of a semi-submersible platform, including naval and structural designs, while Petrobras' engineers worked with them, observing and questioning the design procedures and passing all the information to a Petrobras 'Mirror Team' that replicated independently the designs and followed up queries via the team working with the supplier. Subsequently, the Petrobras teams executed themselves the basic designs of platforms, observed and assisted by the supplier	Asymmetric arrangements in which key R&D and design are carried out by the partners and the focal firm undertakes design and R&D activities with assistance from partners (*Level 2*)	The '*division of labour in knowledge production*' was classified as *Level 2* if responses indicated that (a) 'asymmetric external arrangements' were present and the company undertook design or R&D activities with assistance from partners, but (b) 'symmetric arrangements' and 'asymmetric internal arrangements' were not present
		The division of tasks in the network in *basin analysis and modelling* (1992–1996) involved each partner, including Petrobras, undertaking complementary R&D for developing 3-D basin simulators. For instance, IBM and PUC-Rio developed a 3-D mesh generator and algorithm to develop the computer programs dealing with the geological dynamics of sedimentary basins. Petrobras developed the geological model of the Recôncavo Basin as a prototype for the simulator, and COPPE developed geological models and simulations of basin dynamics. Petrobras coordinated the interfaces and integrated the different knowledge elements of the project	Symmetric arrangements in which the firm and partners undertake specialised R&D and design tasks in the collaboration; some continuing asymmetric arrangements with network partners (*Level 3*)	The '*division of labour in knowledge production*' was classified as *Level 3* if responses indicated that (a) 'symmetric arrangements' were present, and 'asymmetric external arrangements' may also be present, but (b) 'asymmetric internal arrangements' (see Level 4 indicators) were not present
		The division of tasks in the network in *multiphase pumping systems* (1997–early 2000s) combined arrangements in which (i) Petrobras undertook core R&D in the collaboration (for instance, in subsea multiphase flow meters) and transferred the results to other oil companies; (ii) each partner in the collaboration undertook specialised R&D activities in different sub-systems and Petrobras acted as coordinator and system integrator while also undertaking specialised in-house developments; and (iii) a research organisation undertook the bulk of the R&D on a different flow meter concept from the one pursued by Petrobras and Petrobras had access to the results of the project	Symmetric arrangements (both the focal firm and partners undertake R&D and design tasks); asymmetric external arrangements (tasks carried out mostly by partners); and asymmetric internal arrangements (tasks in the collaboration are undertaken mainly by focal firm) (*Level 4*)	The '*division of labour in knowledge production*' was classified as *Level 4* if responses indicated that (a) 'asymmetric internal arrangements' were present in addition to 'symmetric arrangements' and (but not necessarily) 'asymmetric external arrangements'

Note: This example can be used to illustrate how intra-period differentiation between 'dominant' and 'emerging' forms was recognised and dealt with. If interview responses indicated that the type of activity or other network property in a given technological area had changed to another level during a period, but had not become the dominant pattern, the relevant taxonomic level was identified as an 'emerging' characteristic of that network in that period. So, in this example, starting from the second half of the 1992–1996 period, the wet Christmas tree network also included the reverse transfer of knowledge about an in-house wet Christmas tree concept from Petrobras to a partner (a feature of Level 4), and the network property was classified as demonstrating an emerging Level 4 characteristic by the end of the period.

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