SEWPS

SPRU Electronic Working Paper Series

Paper No. 120

Change, Coordination, and Capabilities

Andrea Prencipe
(SPRU, and University d'Annunzio, Pescara)

August 2004

SPRU
Science and Technology
Policy Research

The Freeman Centre, University of Sussex,
Falmer, Brighton BN1 9QE, UK
Tel: +44 (0) 1273 678936
E-mail: a.prencipe@sussex.ac.uk
http://www.sussex.ac.uk/spru/

Change, Coordination, and Capabilities

Andrea Prencipe

SPRU, University of Sussex, Brighton, UK
Faculty of Economics, University G. d'Annunzio, Pescara, Italy
a.prencipe@sussex.ac.uk

Abstract
Empirical studies on coordination of economic activities focused on the two polar cases of governance mode, namely vertical integration and market exchanges. Whether firms should be vertically integrated or lever market exchanges in the face of change is, however, debated. Two positions have emerged. Some scholars argue that the vertically integrated firm is the appropriate mode of coordination when change occurs, while market exchanges are more appropriate for dealing with stable contexts (Teece, 1996). On the other hand, Harrigan (1984, 1985) contends that firms should rely on market exchanges when technological change renders upstream capabilities obsolete. Based on two case studies of the aircraft engine industry, this paper introduces the concept of *systems integration* as the primary coordination mechanism in-between markets and hierarchies that firms employ to cope with change. The focus is on multitechnology settings. Multitechnology, multicomponent products intensify the coordination efforts for firms developing them and therefore provide a vantage point to study coordination modes in the face of technological change. The paper argues that systems integration, as a coordination mechanism, comprises a set of different technological and organizational skills, ranging from component assembly through the understanding and integration of the technological disciplines underlying a product, to project management. It shows that from a competitive point of view, systems integration is most appropriately understood as knowledge integration. *Systems integrating firms* are understood as those organizations that set up the network of actors involved in the industry and lead it from an organizational and technological viewpoint.

Acknowledgements
This paper draws heavily on joint research and writing with my co-authors Stefano Brusoni and Keith Pavitt. The author would like to acknowledge financial support from the European Union Directorate for Research, within the context of the Key Action 'Improving the socio-economic knowledge base' as a part of the project 'Technological Knowledge and Localized Learning: What Perspectives for a European Policy?' carried on under the research contract No. HPSE-CT2001-00051.

Introduction

The research tradition on transaction cost economics pioneered by Coase (1937) and further extended by Williamson (1975) posited that coordination of economic activities can be achieved via market exchanges through the price mechanism or by direction within vertically integrated firms through authority. Coase (1937) argued that the only discriminating criterion between the two coordination modes was costs. Williamson (1975, 1987) proposed a set of factors that influenced transaction costs and that were therefore decisive in choosing the appropriate governance mode. These factors were asset specificity, uncertainty, frequency, opportunism, and bounded rationality. Williamson maintained that asset specificity had a predominant influence in explaining where the efficient boundary of a firm should lie.

The two polar cases of coordination modes discussed in transaction cost economics became the focus of empirical research that studied coordination in the face of technological change. Two positions have emerged. Some scholars argued that when change occurred the appropriate mode of coordination was the vertically integrated firm, whereas market exchanges were more appropriate for coping with stable contexts (Afuah, 2001; Teece, 1996). Other researchers have suggested otherwise. Harrigan (1984, 1985) contended that vertical integration was not the appropriate coordination mode when technological change rendered upstream capabilities obsolete. By relying on market exchanges, firms might exploit relationships from a variety of suppliers rather than confining themselves to one internal relationship. Afuah (2001) suggested that further research should look at the nature of governance modes other than markets and hierarchies in the face of technological change. His suggestion relied on the fact that the dummies he used to control for the role of alliances were highly significant.

By studying coordination modes in-between markets and hierarchies and attempting to reconcile the two apparently contradicting viewpoints, this paper attempts to make a step in the direction suggested by Afuah. Based on two case studies of the aircraft engine industry, this paper introduces the concept of *systems integration* as the primary coordination mechanism in between markets and hierarchies that firms employ to cope with change in multitechnology settings and specifically to reconcile the needs for variety generation, a typical feature of markets, and prompt responsiveness, a typical feature of hierarchies. I have chosen to study multitechnology, multicomponent products, because they intensify the coordination efforts for firms developing them (Granstrand *et al*, 1997; Patel and Pavitt, 1997). The large (and increasing) number of components and technologies cannot be managed within the firm's organizational boundaries. Consequently, the coordination of external sources of components and technologies and their integration with internally produced ones becomes paramount for the successful development of new products and processes. From a dynamic point of view, multitechnology, multicomponent products are better conceptualized as a continuous flow of innovations deriving from different, distant and often intertwined, technological paths. Their evolution, therefore, derives from the joint interaction of a variety of technological fields, so that the most important strategic problem facing companies developing such products resides in the need to coordinate change across technological fields and organizational boundaries. Multitechnology settings therefore provide a vantage point to study coordination modes, particularly in the face of technological change.

The paper argues that systems integration as a coordination mechanism comprises a set of different technological and organizational skills, ranging from component assembly through the understanding and integration of the technological disciplines underlying a product, to project management. It shows that from a competitive point of view, systems integration is most appropriately understood as knowledge integration. *Systems integrating firms* are understood as the organizations that set up the network of actors involved in the industry and lead it from an organizational and technological viewpoint.

The paper is organized as follows. The next section reviews literature on coordination modes. The research method is then presented, followed by data interpretation. A discussion section deepens the concept of systems integration as a coordination mode in-between markets and hierarchies. A conclusion closes the paper.

Literature review and hypothesis

Literature on theory of the firm mostly focused on the relative advantages of two main coordination modes, namely market exchanges and hierarchies. The distinctive advantage of the traditional coordination modes lies in their inner workings. While markets are variety generators through firms' division of labor, firms are generators of specialized knowledge (Kogut, 2000). Markets allow the exploration of distant learning trajectories pursued by independent firms. The outcome of firm division of labor is differentiation. Firms, on the other hand, focus on and coordinate specific learning avenues and acquire specialized knowledge. Firm learning trajectories, however, are limited and limiting in the sense that firms explore in the surroundings of their knowledge bases (Nelson and Winter, 1982). This deepens specialization, but reduces variety generation. Liebeskind (1996) also argued that firms had advantages over markets because they avoid the leakage of proprietary knowledge. Firms, by reducing the observability of knowledge and its products, protected knowledge from imitation.

Scholars who looked at the relationships between coordination and change have emphasized the advantages of both coordination modes. Some authors found that while the price mechanism was more efficient in relatively stable contexts, firms emerged as superior coordinative modes when change affected the competitive dynamics. Firms through authority provided faster responses than markets to changing competitive and technological conditions. Argyres (1995) analyzed the merits of integrated and disintegrated procurement strategy in Ford and GM and found that the integrated response by Ford proved superior to GM's disintegrated one. The superiority of hierarchy as a coordination mechanism as opposed to decentralized market was also found in service-based production. Drawing on a longitudinal study on the US mortgage banking industry, Jacobidies (2002) argued that in-house retail production was more appropriate than market (i.e. the use of outside brokers) when the provision of a new service (e.g. a loan) required processing non-standard information. In-house retail production was a more responsive coordination device in information-rich production.

Other scholars have suggested otherwise. Market exchanges are more suited coordination modes when rapid technological change affects firm competitive dynamics. If vertically integrated, firms might be locked out of new technologies developed by external suppliers. Harrigan (1984, 1985) found that it is not advantageous for firms to be vertically integrated in the face of technological change. Rapid technological change rendered obsolete a firm's upstream capabilities. Hence, firms are better off leveraging market relationships to exploit a larger number of opportunities offered by independent external suppliers. Based on the transaction cost economics argument, Balakrishnan and Wernerfelt (1986) reached similar results. Rapid technological change rendered investments in technologies obsolete and in turn their expected profitability. A low expected profitability entailed less bargaining and hence fewer hold ups and transaction costs. If transaction costs are low, the benefits of vertical integration are reduced.

Coordination and component-level changes

Studies on the relationships between technological change and coordination mode identified two dimensions of change (Brusoni, 2003; Brusoni, Prencipe, and Pavitt, 2001).[1] The first related to change in the relationships among components composing a product. The second dimension related to the changes in the knowledge bases underpinning a component. It referred to the impact that a technological innovation had on firm and supplier capabilities. The appropriateness of governance modes (markets and hierarchies) and their underlying coordination mechanisms (price and authority, respectively) was therefore said to be contingent upon changes on components' interactions (Teece, 1996) or the impact of a technology innovation on a firm's and its suppliers' capabilities (Afuah, 2001).

As regards the first dimension, two main types of innovation were identified, namely modular (or autonomous) and architectural (or systemic) (Henderson and Clark, 1990; Teece, 1996). A modular innovation is a change in the core design concept of a component that does not affect its relationships with others. Modular innovations are in fact characterized by standardized interfaces with existing components and technologies. An architectural innovation is defined as a change in the relationships between a product's components that leaves untouched the core design concepts of components (Henderson and Clark, 1990).

The different features of architectural and modular innovations call for distinct coordination modes. Modular innovations were found to be easily coordinated via market mechanisms, since their integration with existing components rested on well-defined interfaces. When the interfaces among components become well known, the interactions between them can be studied, codified, elaborated, and shared. These interfaces are usually codified in industry standards (Chesbrough and Teece, 1996). As this knowledge becomes codified, the price system is increasingly able to coordinate transactions within the architecture, and the coordination of the system shifts from inside the firm to the outside. In this case, firms can adopt organizational forms that lever market exchange rather than hierarchies. These organizational forms, also labeled modular or virtual corporations, were found more responsive than integrated ones in that they can use market-based incentives to quickly access the technical resources they need (Chesbrough and Teece, 1996; Sanchez and Mahoney, 1996; Teece, 1996). Integrated firms fall far short of duplicating such quick response mode.

Firms are better suited to manage architectural innovations instead (Chesbrough and Teece, 1996). Architectural innovations could be realized only in combination with complementary innovations and therefore required significant changes and fine-tuning to other components and therefore continuous information exchange and sharing across the units of production since they redefine the interfaces "throughout an entire product system." (Chesbrough and Teece, 1996: 68) When an architectural innovation is introduced, the market loses its lead precisely because of its scarce ability to coordinate the required exchange of information and to settle conflicts over integration issues claimed by different firms. By contrast, firms are better suited in this case. Scale and integration could turn out to be advantageous when complementary innovations are required to leverage a new technology.

Hypothesis 1. Modular innovations are better managed through modular forms of organization that lever the superiority of market exchanges. Architectural innovations (i.e. changes in the relationships among components) call for a hierarchical mode of coordination.

---

[1] These two dimensions can be combined to identify different typologies of change (e.g. architectural – competence destroying innovation).

Coordination and knowledge-level changes

Tushman and Anderson (1986) introduced the concepts of competence-destroying and competence-enhancing technological innovations. Competence-destroying innovations are technological discontinuities that require radically new skills and knowledge bases to be mastered. They may create an entirely new product class (automatically-controlled machine tool) or substitute for an existing class of product (e.g. the shift from mechanical cash registers to electronic point-of-sale registers). When a competence-destroying innovation is introduced, the skills and knowledge of incumbent firms and their suppliers are rendered obsolete. Competence-enhancing innovations are instead improvements (in products and/or processes) based on existing skills and knowledge. Such improvements "do not render obsolete the skills required to master the new technologies." (Tushman and Anderson, 1986: 442)

Afuah (2001) deepened our understanding of the relationships between coordination modes and competence-destroying innovations. He studied the dynamics of the boundaries of firms producing computer workstations in the face of a competence-destroying technological innovation, namely the shift to reduced instruction set computer (RISC) technology. The adoption of RISC technology rendered obsolete the capabilities of firms manufacturing computer stations and their suppliers. Afuah found that firms that were vertically integrated in the RISC technology performed better than non-vertically integrated ones. The superior performance of vertically integrated firms was due to two main dimensions linked to the development of a new technology. First, the knowledge underpinning the new component may well be tacit, hence frequent, in-person interactions between people and units developing them are required. Second, compliance by administrative fiat would reduce room for opportunism (generated by the uncertainty underlying the new technology) and protect the firm from disputes with external suppliers.

Hypothesis 2. Competence-destroying innovations (i.e. changes in the components' underlying knowledge basis) call for hierarchical coordination mode.

Research method

Two case studies are presented below. The first is on the aircraft engine external gearbox. The second case study is on the aircraft engine control system. The two case studies were chosen for two main reasons. The first relates to the larger product these components are part of, namely the aircraft engine. Aircraft engines are multitechnology, multicomponent products. The multitechnology, multicomponent nature of the aircraft engine enables the analysis of the capabilities needed by the engine manufacturers to coordinate the development of such a complex product. The second reason is that over the last thirty years the engine control system and the external gearbox have been characterized by two very different dynamics at the technological level. In the control system, a radical shift occurred in its underlying technologies: from hydromechanics to digital electronics. This shift is particularly interesting to study from a strategic viewpoint because aircraft engine manufacturers faced an important decision on the appropriate coordination mode of managing the new technology. The external gearbox instead relies on relatively stable technologies (tribology and fluid mechanics). It is considered a modular, stand-alone sub-system of the engine, and it is designed and produced by specialized suppliers.

The study draws on qualitative and quantitative data collected during a four-year field study of the aircraft engine industry. Data were gathered through research in both primary and secondary sources. These distinct types of data were employed in this study to establish construct validity (Yin, 1994). Multiple data sources enabled me to obtain stronger substantiation of constructs by triangulating evidence across cases.

Primary sources of qualitative data included a total of 27 interviews with company representatives.[2] For the control system case study, 12 face-to-face in-depth interviews were conducted with representatives of one engine manufacturer and four engine control system suppliers based in Europe and the US. Interviewees included the Chief Control System Engineer, the Head of the Control System Division of both engine manufacturer and suppliers, and a Chief Software Engineer of the engine manufacturer. For the case of the gearbox, 11 face-to-face interviews were carried out with representatives of one engine manufacturer and two gearbox suppliers based in Europe. Interviewees included Technical Directors and Chief Designers. Interviews were semi-structured and lasted about three hours. Interviewees were asked questions about the extent of the division of labor between engine manufacturer, and first- and second-tier suppliers.[3] Hand written notes were taken during the interviews in order to collect as much evidence as possible. These notes were transcribed soon after conducting the interviews. This enabled a preliminary scan of the interview data.

Secondary sources of qualitative data included company annual reports, trade journals, specialized engineering journals, and industry reports on the world's three largest engine manufacturers. In the trade literature, these three engine manufacturers are called the Big Three or the Primes. They dominate the large turbofan industry, since they hold about 90% of the world market. The names of the firms have been disguised for confidentiality reasons and labeled Company A, Company B, and Company C. These data were used to provide background information and to sketch an overall picture of the technologies underlying the engine's gearbox and control systems.

Primary source of quantitative evidence came from a sector specific database. I used an original data set designed by rearranging the US Patent Office classes. The database encompassed patents granted to aircraft engine manufacturers and component suppliers between 1977 and 1996. Patents granted to suppliers whose 50% or more equity share is owned by the engine manufacturer or by the same holding company have been ascribed to the engine manufacturer. Patents were rearranged according to a detailed sector specific taxonomy that relates each patent to a specific engine component or subsystem. The validation of the taxonomy was carried out through extensive interviews with two primary examiners of the US Patent Office and firm engineers interviewed during the fieldwork research. The use of patent data as a proxy measure of companies' technological capabilities has its limitations, as discussed in the literature (Scherer, 1988; Wyatt, Bertin, and Pavitt, 1988). In particular, propensities to patent vary among firms, sectors, and countries. In our analysis, we attempted to overcome some of these limitations. First, we analyzed firm patenting activities within the same sector. Second, through interviews we collected qualitative data to validate the accuracy of the results of the patent analysis.

The investigation of companies' patenting activity was carried out through the analysis of their revealed technological advantage (RTA) index. The RTA of a company in a specific technological field is given by its US patent share in that field, relative to the firm's overall US patent share in all fields. In other words, the numerator of the RTA index is given by the number of US patents held by a firm in a technological field divided by the number of US patents in that technological field granted to companies in the same industry. The denominator is given by the firm's total number of US patents in all technological fields divided by the number of US patents assigned to firms in all technological fields in the industry in question. In symbols:

$$RTA_{ij} = (P_{ij}/\sum_j P_{ij})/(\sum_i P_{ij}/ \sum_{ij} P_{ij})$$

[2] These two case studies are part of a larger 4-year field study which looked at the dynamics of the division of labor in the aircraft engine industry (Ref. omitted).
[3] See Appendix A for a sample of questions asked during the interviews.

Where:
P_{ij} = number of US patents granted to firm *j* in sector *i*.

The RTA index has been used to study inter-country comparisons (Balassa, 1965; Soete, 1981; Cantwell, 1989; Laursen, 1998) as well as intra-industry and inter-firm comparisons (Patel and Pavitt, 1997; Cantwell, 1991, 1993). Though the RTA may lead to understand it as an index that measures a firm's advantages in a specific technological field, many scholars argued that it should be better considered as an index of comparative specialization of one firm with respect to others across a range of identified technological fields (Laursen, 2000; Geuna, 2000). The RTA index varies around unity so that values greater than 1 reflect a comparative specialization of the firm in a particular technological field in respect to other firms in the same industry.

The use of this index overcomes some of the limitations of the use of patent statistics as a proxy measure of companies' technological capabilities. As regards the different propensity to patent that characterizes technological fields and firms, the RTA is normalized in the numerator for inter-field variation and for international inter-firm differences in the denominator. According to Cantwell (1991, 1993), there may still be inter-field variations in inter-firm propensity to patent. Some firms may be more likely to patent in some fields than others, and *vice versa*. Cantwell suggested that this intra-firm variance is lower than the inter-field difference, however. Therefore, "on relatively large numbers the propensity to patent of a given firm in any sector [i.e. technological field] cannot be expected to have any systematic bias as compared to that firm's notional average propensity to patent and the notional average propensity to patent of all firms in that sector [i.e. technological field]" (Cantwell, 1993: 221).

In order to improve the quality of the research, for the analysis of the empirical evidence two tactics were employed (Lee, 1999; Yin, 1994). First, qualitative insights provided by interviewees proved to be fundamental for understanding the knowledge requirements underlying the patterns of division of labor described by the quantitative data. This stage has enabled us to identify and evaluate patterns as they emerged from *within case* (Eisenhardt, 1989). Second, I employed the *pattern-matching tactic* suggested by Yin (1994: 106), "Such a logic (Trochim, 1989) compares an empirically based pattern with a predicted one (or with several alternative predictions)". The use of this tactic assumes the development of rival explanations involving mutually exclusive independent variables. The use of the pattern-matching tactic strengthens the *internal validity* of the research.

For the case of the control system, a draft of the empirical account was sent to key informants (one representative of the engine manufacturer, and representatives of three suppliers) and four follow-up interviews were conducted to clarify misunderstandings, discuss and comment on the accuracy of the account and hence validate our research. This tactic helped establish the *construct validity* of the research (Yin, 1994). For the gearbox case study, the results of the analysis were illustrated and discussed in a further face-to-face interview with a senior technical manager of a supplier. The gearbox case study was also emailed to the representative of the engine manufacturer interviewed who agreed (via email) with the main results of the case.

Results

Coordination and component-level changes: the case of the gearbox

The external gearbox has relied on the same stable technologies (tribology, fluid mechanics) for the last twenty years. The maturity of these technologies has enabled engineers to understand, articulate, and modularize the interfaces between the engine and the external gearbox. Very competent specialized suppliers emerged and engine manufacturers outsourced to them the design and manufacturing of the gearbox subsystem. Specialized suppliers of external gearboxes, such as

Fiat Avio, became key partners of engine manufacturers in the development of new engines to the extent that they shared risks and revenues of engine development programs.[4]

As the theory would have predicted, the modular interface between engine and gearbox, and the stability of the technologies underpinning the latter gave way to a well-defined pattern of division of labor between engine manufacturers and gearbox specialized suppliers. While engine manufacturers concentrated their efforts on the architecture of the gearbox, the specialized suppliers focused on the design and manufacturing of the gearbox and related components and subcomponents. Hence, a modular pattern of division of labor emerged and supported the distinct learning trajectories of engine manufacturers and gearbox suppliers. Engine manufacturers and gearbox suppliers reaped the benefits of modularity in products as well as in organization.

At the beginning of the 1990s, this modular relationship between engine suppliers and manufacturers started falling apart. When engine manufacturers launched the new large commercial turbofan engines to meet the thrust requirements of the Boeing 777, the engine-gearbox interface started causing problems. For the launch of the new engines, the engine manufacturers adopted different governance modes. Company A set up a collaborative agreement with a gearbox supplier. Specifically, it relied on a long-standing relationship with a supplier, which bought a stake in the new engine development program and became a risk and revenue partner. Company B relied on an internal supplier belonging to its industrial conglomerate. Company C relied exclusively on an ordinary contract. The engines of Company A and Company C experienced problems related to the external gearbox. The following quotes were taken from *Jane's Aero Engines* (1997).

> "In April/May 1997 trouble hit the step-aside gearbox which transmits the drive from the radial power-take-off shaft from the front of the HP compressor to the sloping shaft driving the external accessory gearbox…. This unit suffered bearing seizures caused by inadequate lubrication resulting in the grounding of the A330s of Cathay Pacific and Dragonair. Modification kits were quickly supplied."

> "In March 1997 the airline suspended transatlantic ETOPS operations when chip detectors revealed debris to bearings in the accessory gearbox. [The engine manufacturer] redesigned the gearbox, and the airline reduced the inspection interval."

The failures affected both the engine whose gearbox had been sourced from a supplier through an ordinary contract (Company C) and the engine whose manufacturer (Company A) and gearbox suppliers worked under a partnership agreement and their development teams were co-located. Instead, the engine of Company B performed well.

The failure of the engines of Company A and Company C found its rationale in the fact that the engine manufacturers and suppliers focused their efforts exclusively on their modular role to the extent that their distinct learning trajectories became air tight and eventually divergent. Specifically, the modular interface and the stability of the technology underlying gearboxes (alongside cost pressures) induced Company A and Company C to drastically diminish their involvement in the development of the gearbox in new engine development programs. This was not followed up by any investment aimed at maintaining the technological capabilities necessary to integrate the gearbox back into the engine system. The combined effects of these two factors caused a divergent gap between the technological capabilities of the two engine manufacturers and their specialized suppliers. The new large turbofan engines were characterized by unprecedented

[4] In the trade literature suppliers that take on a stake in terms in programs dedicated to the development of new engines are labeled risk and revenue sharing partners.

thrust requirements. Their exceptional size compared to previous engines brought about scale effects that neither engine manufacturers nor suppliers were able to manage within the well defined pattern of division of labor that sedimented over time. The Technical Director of Company C confirmed the aforementioned interpretation "We kept outsourcing gearboxes, and we have lost the ability to integrate them!"

The experience of Company A pointed to the fact that even in relation to components that relied on the same stable technology, whose interfaces were modularized, and whose development was carried out under a collaborative agreement, a minimum threshold of technological capabilities in relation to the outsourced components was required for the success of the joint work.

The modular learning trajectories of Company A and Company C could also be observed by looking at their patent portfolio. Table 1 reports on the RTAs related to the patents obtained in gearbox technologies of the three engine manufacturers between 1977 and 1996. RTAs provided an approximate indication of the specialization of a firm's capabilities in gearbox technologies relative to other competitors. The table shows that between 1987 and 1996 Company A's RTA remained relatively stable though below unity, while the RTA of Company C also fell below unity. In other words, after the outsourcing of the design and manufacturing of gearboxes, the learning trajectories of Company A and Company C concerning the specific component became modular and therefore they lost the capability to integrate it back into the engine. The RTA of Company B increased between 1987 and 1996. Company B through its internal supplier kept investing in gearbox-related technologies to maintain the technological capabilities to develop and manufacture them.

[Table 1 about here]

The results of this case study shed light on the relationships between component-level changes and governance mode. According to the theory, market exchanges are better suited to coordinate modular innovations, while architectural innovations should be governed through vertical integration. The case of the gearbox illustrated, however, that a modular product design may not well embed all the future interactions across components. In other words, unpredictable component interdependencies may well emerge and cause integration problems in multitechnology products. Hence, firms require integration capabilities to deal with such changes. Vertical integration proved to be the appropriate coordination mechanism in the face of change. As the case of Company B showed, an internal supplier dedicated to the development and manufacturing of components provided the enabling capabilities to engine manufacturers to solve the problems.

Coordination and knowledge-level changes: the case of the control system

Early aircraft engine control systems were based on hydromechanical technologies. When hydromechanical control systems reached technological maturity, engineers were able to understand, articulate, and modularize the interfaces between the engine and the hydromechanical control system. The introduction of digital electronics progressively enlarged the role, importance, and functions of the engine control system as well as its interfaces with the other engine components and the airframe. The radical technological shift led to a functional shift. Digital electronics is a fast moving technology. This high rate of advance enabled the embodiment in the control system of a large and increasing number of functionalities previously carried out by the pilot. The digital control system became the brain of the engine. Although digital control systems interacted with a higher and enlarging number of engine components, the so-called interface software governed these interdependencies. Due to this software component, digital control systems were not application-specific and hardware and software modules could be re-used in different applications (Prencipe, 2000).

Although they competed with similar products in similar markets, the three engine manufacturers initially adopted different coordination modes in relation to engine control systems. This is consistent with the evolutionary approach to the theory of the firm as discussed by Nelson (1991). When engine controls were based on hydromechanical technologies, Company A was characterized by a vertically integrated structure. As the technology matured, it started outsourcing its design and manufacturing. Company B maintained its exclusive engine control system supplier throughout the life cycle of the hydromechanical trajectory. Company C relied heavily on a supplier, whose relationship became weaker when the technology stabilized.

In the 1980s, when digital electronics emerged, Company A was initially vertically integrated in relation to the digital components associated with the control system. It then sold its internal supplier in 1996 to whom it delegated the production of control system components but, at the same time, maintained in-house capabilities for designing the architecture of the control systems, integrating the components into the engine, and monitoring further development in digital electronics. Company B continued its policy of exclusive collaboration with an internal supplier. Unlike its competitors, Company C always maintained arm's-length market relationships with its suppliers. Because of lack of in-house technological capabilities, it took longer than its more integrated rivals to identify the developments of digital electronics and experienced problems in the integration of this new fast-moving technology. Consequently, Company C did not decide to vertically integrate to master the new technology. It developed in-house technological capabilities in digital electronics and built links with external specialized suppliers and particularly with universities with a proven track record of excellence in digital technologies. Company C's decision not to vertically integrate in the end proved successful since it eventually caught up with its competitors.

Although vertical integration (or exclusive control of a supplier) proved to be a successful strategic option for coordinating a competence-destroying innovation, as the cases of Company A and B showed, it was not the only viable one. With some delays, Company C managed to master the competence-destroying innovation through appropriate in-house investments in digital electronics and at the same time through leveraging external technological capabilities in suppliers and particularly in universities. In 1990 Company C institutionalized research collaboration with national universities through the creation of long-term, research-based partnerships with selected university departments whose aim was to maximize the effectiveness of capability acquisition. Each partnership supported a well-defined research field through the creation and maintenance of the company's core capabilities.

Do modular products design modular organizations?

Notwithstanding the increasing modularization of control systems, brought about by the advent of digital electronics and particularly software, the division of labor between aircraft engine manufacturers and control system suppliers did not become clear-cut. Using US patent statistics as a proxy measure of technological capabilities, we attempted to understand in depth the evolution of the learning trajectories in digital electronics, as it became the new dominant technology. Table 2 reports on the RTA of the control system-related patents in the three companies under scrutiny. This comparison enabled an assessment of the dynamics of changes in the relative importance of control system technologies across the firms analyzed.

[Table 2 about here]

Company A's RTA showed a decrease in the last decade analyzed. An RTA lower than one also reflects a change in the pattern specialization of the firm in the sense that control system technologies became less important for the firm's overall policy. Interview data gathered from the specialist supplier sold in 1996 confirmed that Company A still designed the overall architecture and acted as the integrator of the control system components. In Company B, Table 2 shows relatively stable RTA indices that reflect the vertical integration structure adopted by the firm, notwithstanding the increasing modularization of the interface between the engine and the control system. Although it did not design or produce control systems, Company C exhibited a sharp rise in the RTA index in the first two periods analyzed. Extensive interviews confirmed that this pattern reflects Company C's efforts to develop technological capabilities to coordinate pro-actively its network of suppliers. While the latter maintained their independence, Company C was actively and increasingly involved in their control system development efforts. This was due to the necessity to evaluate design options with the fast rate of change characterizing digital electronics.

The case of Company C is particularly telling in respect of systems integration as a coordination mode and to understand whether the modular interfaces of the digital control system also entailed modular interface among engine manufacturers and specialized suppliers. In order to better understand the nature of systems integration, I adopted the distinction between architectural knowledge and component knowledge put forward by Henderson and Clark (1990) and borrowed, and extensively used, by management scholars studying modular product design (Sanchez and Mahoney, 1996). A break-down into 'Architecture', 'Sub-architecture', 'Functional', and 'Component' groups was carried out by the Head of Engine Control System of one the world's largest engine manufacturers on the basis of the content of the abstract of each patent. 'Architecture' patents were those whose abstract described how components were arranged in a system. 'Sub-architecture' patents were those whose abstract described how components were arranged in a subsystem. If the main content of the patent abstract described functional behavior of a system, i.e. what the system does, I labeled patents as 'Functional'. 'Physical' patents were those whose abstract concerns physical description of an item or a subsystem, i.e. what the system looks like.

Although Company C had the largest number of architectural patents, it did not focus only on the architecture of the control system (Figure 1). Rather, it took patents out in the 'Physical' and mainly in the 'Functional' categories. The interesting point is that this particular aircraft engine manufacturer had not designed or manufactured any components of the engine control system. It was required, however, to have an understanding of the functioning of the units in the engine control system. Such an understanding was a *sine qua non* to integrate the different components together and within the engine system. Therefore, such technological capabilities allow the engine manufacturer to specify, assess, and test externally produced components. Interview data clearly revealed that the firm never engaged in an effort to develop the capabilities necessary to design, manufacture, and assemble all the hardware and software components that made up the digital control system. Rather, the emphasis of Company C's technology policy always fell squarely on the necessity to develop in-house *understanding* of the underlying bodies of knowledge and ensuing system behavior, rather than on the *activities* of design and assembly.

[Figure 1 about here]

The relevance of maintaining and nurturing systems integration capabilities regarding fast-moving technologies was also clear by looking at the hierarchical division of labor between engine manufacturers and suppliers in the development of control systems. Company C did not relinquish relevant phases of the definition of the control system. The activities relating to the requirements definition cascade of the control system are carried out by different teams all belonging to the engine manufacturer. The engine manufacturer's involvement differs from activity to activity and according to the importance of the component. In the case of hardware, the extent of its involvement may well stop at the level of specifications, and design and manufacture are contracted out to specialized suppliers. In the case of software, while the *core software* that governs the engine and is pivotal for the overall engine performance is defined, specified, designed, and written by the engine manufacturer, the *interface software* that includes functions such as signal validation, control system fault detection, and airframe inputs and outputs is only defined and specified in terms of requirements.

One further comment relates to the economic nature of the decisions concerning the development and maintenance of systems integration capabilities. Such decisions do entail a trade-off between resources (i.e. time and costs) and opportunity cost (of not maintaining in-house a minimum threshold of technological capabilities). Engine manufacturer involvement in the development of the control system may therefore change from program to program to accommodate both resource constraints and knowledge necessity. In some engine programs, it may confine its involvement to requirement definition. In the subsequent programs, it may take on most of the phases involved in the development of the control system in order not to lose its systems integration capabilities. The following quotes well underline such trade-off.

> "We always integrate the control system within the engine. For economic reasons we may decide not to do it, but for technical reasons we have to do it".

> "It is more a case of a business decision to reduce our responsibility at the detailed design level, but we will maintain some capability and a fundamental understanding of whatever we put out."

Discussion and conclusions

Systems integration as coordination mechanism in-between markets and hierarchies

Afuah (2001) called for further empirical research to analyze how firm boundaries evolve in the face of technological change. He also called for empirical studies on other coordination modes besides the traditional dichotomy vertical integration vs. market exchanges. Taking a first step in this direction, this paper examined how firms operating in multitechnology settings respond to technological change. This study introduced the concept of systems integration as a coordination mechanism in-between markets and hierarchies of firms that produce multitechnology, multicomponent products. Specifically, we argue that two dimensions of systems integration are relevant for firms developing multitechnology, multicomponent products.

The first dimension relates to firm capabilities to integrate components designed and manufactured either externally or internally and therefore to handle unpredicted interactions between components. We label this dimension *synchronic* system integration since it mainly relates to firm capabilities to synchronize the work of the networks of suppliers within an existing technology. The synchronic dimension relates to firm capabilities to set the concept design, decompose it into subsystems and components, and delegate design and manufacturing tasks to suppliers. In particular, synchronic systems integration refers to the capabilities to refine, adapt, and optimize (stretch) existing architectures through the development of derivative products in order to cater for different customer requirements. The capability of manufacturers to stretch architectures to develop derivative product is a function of the degree of modularity of the architecture itself. Modularity enables manufacturers to use common product platforms to target different niche markets. It also allows manufacturers to considerably improve the performance of existing architectures through the introduction of incremental and radical technological innovations at the component level.

The argument put forward by Sako (2003) in her study on modularization in the auto industry supports the results of the case study of the aircraft engine external gearbox. Sako argued that, although the basic architecture of an automobile has become fairly stable, there are many aspects of the linkages within the electro-mechanical architecture that are not yet fully understood. Achieving a particular noise/vibration/harshness (NVH) level at different maximum speeds requires a deep understanding of the ill-defined interactions between the body, chassis, engine, and drive-train. Despite having outsourced the design and manufacture of the body, chassis, cockpit, drive-train and sometimes even the engine, only car manufacturers have maintained the integration capabilities necessary to obtain a workable automobile. Even in relatively stable contexts characterized by modular architecture, firms maintain some systems integration capabilities that enable them to integrate components designed and manufactured by external suppliers.

The interpretation of systems integration as *synchronic* capability finds its historical antecedent in the study of the Polaris System Development carried out by Sapolsky (1972). Indeed, the title of Chapter 5 of Sapolsky's book is *The Synchronization of Progress in Several Technologies*. Sapolsky argued that the primary objective of the Polaris project was the construction of a submarine system rather than advancement of its underlying technologies. In his words, "The deployment of the Polaris submarines required the *synchronized development of a dozen different technologies*….To build a system that involved interdependent progress in a dozen technologies was, however, unprecedented" (p. 137, emphasis added). He then went on to explain

> "[T]he product of the development, the early deployment of the FBM [Fleet Ballistic Missile] submarine, was a greater and more uncertain achievement than the sum of its parts would lead one to believe. It was the synergistic effort or the tying together of progress in diverse technologies on a compressed schedule that was both the challenge and the breakthrough in the FBM Program and not the progress in any of its component elements" (p. 138).

The case study on control systems pointed to a more dynamic dimension of systems integration. We label this dimension *diachronic* systems integration since it refers to the firm capabilities to coordinate changes. Specifically, these capabilities must be developed for the coordination of change across (a) different bodies of technological knowledge, since different bodies of technological knowledge relevant to production may be characterized by uneven rates of advance; and (b) different organizational boundaries, firms cannot master in-house all the relevant scientific and technological fields. The management of the relationships with and coordination of external sources of technologies, such as universities, research laboratories, and suppliers, becomes therefore a central task for multitechnology firms.

Diachronic systems integration identifies a continuum of technological capabilities ranging from the introduction of incremental architectural innovations to the introduction of fundamentally new product architectures. In the latter respect, *diachronic* systems integration is better understood as a risk-bearing attitude to search and explore alternative paths of product configurations. The introduction of radically new configurations requires major coordination efforts between engine manufacturers, airframers, airlines, and certification authorities.

The results found by Chesbrough (2003) in his study on the hard-disk drive industry are consistent with the concept of diachronic systems integration. He argued that technologies follow a dynamic cycle that goes from integral to modular. In the integral phase, usually the first stage of technological development, the interdependencies between components are fast changing and poorly understood. Architectural innovations occur at this stage, which requires stricter coordination mechanisms. In the modular phase, when the components and their interdependencies are better understood, articulated, and modularized, coordination is better achieved through the markets. Firms that were not ready to adapt in order to keep their organization in tune with the technological phase fall into modularity or integral traps.

Chesbrough argued that one disk drive producer managed successfully the shift from a modular to an integral. Accordingly, the success of Fujitsu was due to its systems knowledge. During the modular phase, like other firms, Fujitsu relied on a decoupled network of external suppliers. Unlike the other firms that fell into the modularity trap, however, Fujitsu maintained systems knowledge through R&D investments in materials and component technology. Fujitsu's systems knowledge enabled the firm to master the new integral technology (i.e. the magneto-resistive head). Chesbrough also argued that also in a possible shift back from the integral to the modular phase, Fujitsu may have taken the appropriate strategic steps in relation to technological investments and organizational set-ups with other companies, in order to align its organizational form to the technological shift. To sum up, both the aircraft engine manufacturer and Fujitsu made heavy investments in systems-level knowledge. They maintained wide technological capabilities well beyond those needed to perform design and production activities. Therefore, outsourcing the production of components does not necessarily entail outsourcing the bodies of knowledge employed to specify, design, integrate, manufacture, test, and assemble them. Increasingly, firms maintain and develop knowledge relying on learning mechanisms other than 'doing' (Pisano, 1997).

Implications for theory

The features of systems integration capabilities discussed in the paper contribute to the emerging literature on the relationships between modularity and the boundaries of the firm. Scholars in this field argued that modularity might well inform organizational design besides product design. Product designs organization, as Sanchez and Mahoney (1996) contended. The case studies presented above provided an alternative view to modularity. Both cases in fact illustrated that modularity was a feature of both components of the aircraft engine product. Modularity did not inform the knowledge boundaries of the firm producing them. Indeed, when it did, the firms ran into problems. Therefore, the product components' interfaces do not necessarily define the relevant knowledge interfaces. In other words, the case studies showed that knowledge boundaries of the firm fundamentally differ from the boundaries of the firm as defined by make-buy decisions.

By disentangling different dimensions of the firm boundaries, this study adds another dimension that helps understand and theorize the boundaries of the firm within the resource-based view of the firm. This theory conceives firms as collections of resources of various natures, whose coordination paves the way to the development of unique organizational capabilities that in turn constitute the basis of a firm's competitive advantage (Penrose, 1959; Grant, 1996). Within this view, each firm has its own distinctive history and capabilities that place a frontier (small or large) around their freedom to maneuver. While this theory proved to be particularly telling in respect to the internal workings of the firm, it failed in correctly theorizing interface capabilities. This study suggests that the nature of the boundaries of the firm is complex and determined by the interplay of product as well as knowledge dynamics. In other words, it shows that the boundaries of the firm are multifaceted and should not be confined to (or confused with) the boundaries of the firm as defined by product interfaces. This is consistent with the work by Takeishi (2002) who put forward the distinction between division of knowledge (knowledge-partitioning) and division of operational tasks (task-partitioning).

This study also contributes to the literature on inter-firm networks. A growing body of theoretical and empirical literature argued that in the last decade the relevance of external sources of component and knowledge for a firm's competitive advantage has increased. Hence, managing external relationships through the development and maintenance of an extensive flow of information across the boundaries of the firm becomes relevant to develop and sustain a competitive advantage. Kogut (2000) argued that networks can combine the advantages of both traditional mechanisms of coordination and therefore can promote variety as well as coordination. Exploiting the knowledge of a network requires a focal firm to be equipped with capabilities that enable it to manage external relationships and therefore to exploit variety (a distinctive characteristic of the market) and use authority to deal with and implement changes (a typical feature of hierarchies).

By fleshing out the characteristics of systems integration capabilities, this study offers a promising perspective in looking into a firm's network capabilities and how they should change during the evolution of a technology. When a new technology emerges and is fast-moving, the control systems case demonstrated that systems integration is a feasible strategic option to master the ensuing competitive changes. Relationships with universities may well be more appropriate here in order to explore new learning trajectories and eventually reconfigure a firm's network.

Implications for management practitioners

The focus of this work on the appropriate coordination mechanism that firms employ to deal with change in multitechnology settings may be of interest to management practitioners interested in improving the dynamic performance of their organizations. Management practitioners are required to be aware of systems integration capabilities as a coordination mechanism in-between markets and hierarchies. Firms need not necessarily be vertically integrated to cope with competence-destroying innovations. Likewise, firms need not be modular concerning their knowledge boundaries. A corollary of this is that decisions to outsource technological knowledge do not follow automatically make-buy decisions related to product components.

The need to develop and maintain knowledge bases beyond a firm's product domain was also found by Liker *et al* (1996) in their comparison of Japanese and US supplier involvement in automotive component design. They found that Japanese automakers were less dependent on suppliers for product development knowledge than US ones. Their study revealed that US automakers were not able to easily replicate a much higher percentage (63% vs. 39.1%) of development effort than their Japanese counterparts. Accordingly, Japanese automakers' competitive advantage in the 1990s lay in their systems integration capabilities that enabled them to develop superior products and outclass their US counterparts in their national markets. This squares with the results of the above-mentioned study by Takeishi (2002). Drawing on an empirical study on automakers' management of suppliers' involvement in product development in Japan, he found that the automakers that performed better in developing new components were those that maintained both architectural and component knowledge in-house. While the actual tasks of design and manufacturing could be outsourced, automakers retained relevant knowledge to obtain better component design quality to perform better than their competitors in terms of product functionalities.

Conclusions and directions for future research

The aim of this paper was to analyze the coordination modes employed by firms to cope with product and technological changes. It focused on two case studies drawn from the aircraft engine industry, a multitechnology, multicomponent setting. Multitechnology settings are particularly interesting for studies on coordination mechanisms for innovating activities. The multitechnology, multicomponent nature of the product poses significant strategic implications for the firm in terms of make-buy decisions, given that technologies and components are too many to be mastered within the boundaries of one single organization, let alone changes in the underlying product technologies.

The two cases studied indicated that firms that developed and maintained systems integration capabilities outperformed their competitors. Systems integration can be considered a coordination mechanism in-between markets and hierarchies. The paper identified two analytical categories of systems integration, namely *synchronic* and *diachronic*. Synchronic systems integration refers to the capabilities required to set the product concept design, decompose it into modules, coordinate the network of suppliers, and then recompose the product within a given architecture. It is argued that from a static point of view, products can be seen as interlocking pieces and the main task of firms is to dovetail the work of suppliers to meet the program deadlines and customer requirements. Diachronic systems integration refers to the capabilities for coordinating changes across technological fields and organizational boundaries in order to envisage and move progressively towards different and alternative paths of product architectures (i.e. new product families) to meet evolving customer requirements.

This paper has focused only on the knowledge dimension of governance modes, and therefore may well miss other important dimensions that characterize these modes and explain their functioning and suitability of governance modes in the face of change. The discussion of the administrative dimension of such modes has only been touched upon. Future research may inquire into the equity structure of governance modes. Also, a longitudinal map of the interactions among the firms involved in the development of new multitechnology products and the background capabilities of scientists and engineers belonging to such firms may further shed light on this issue.

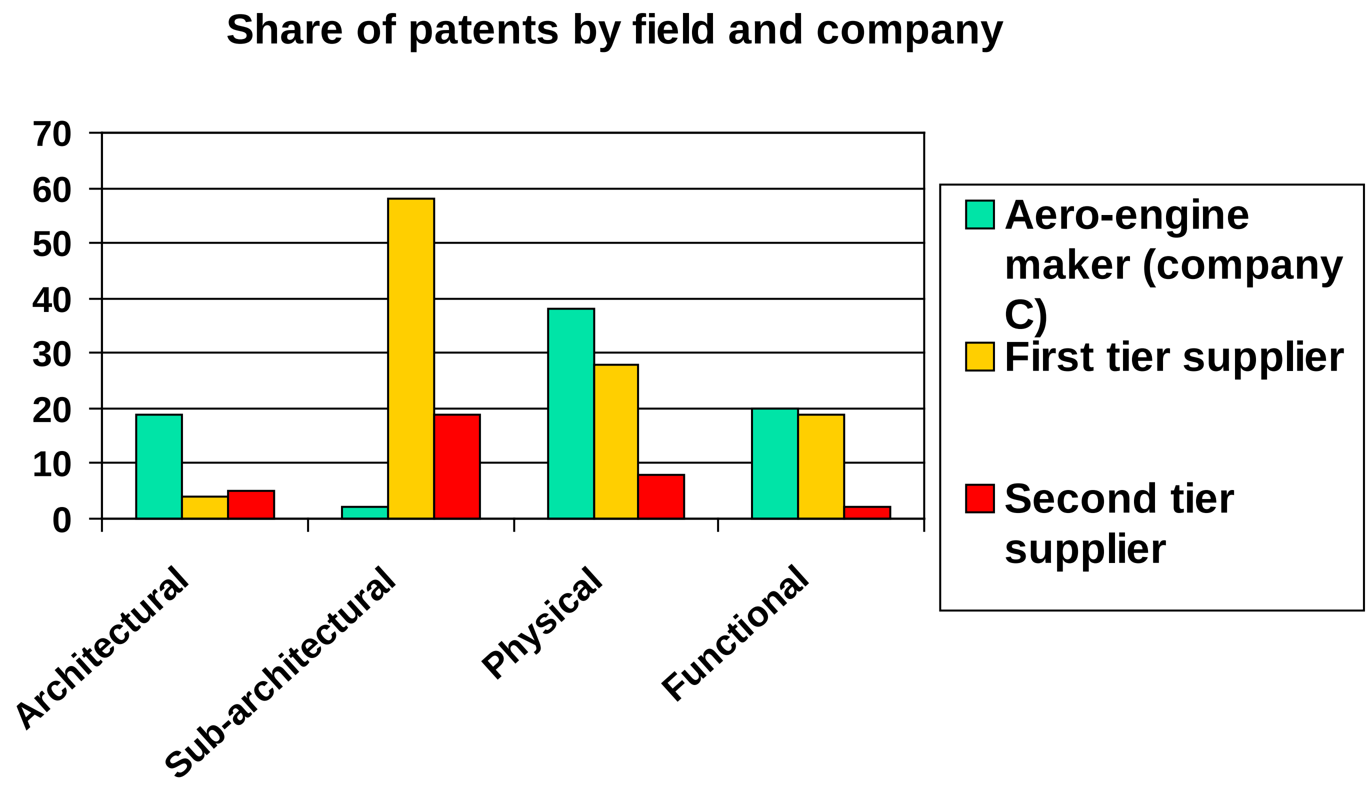
Table 1. Companies' Revealed Technological Advantage (RTA) in gearbox technologies

	Company A		Company B		Company C	
Technological field	**1977-1986**	**1987-1996**	**1977-1986**	**1987-1996**	**1977-1986**	**1987-1996**
Gearbox technologies	0.84	0.94	0.8	1.03	1.15	0.96

Table 2. Companies' Revealed Technological Advantage in control system technologies

	Company A		Company B		Company C	
Technological field	**1977-1986**	**1987-1996**	**1977-1986**	**1987-1996**	**1977-1986**	**1987-1996**
Control system technologies	1.1	0.84	1.1	1.31	0.62	1.08

Figure 1



References

Afuah, A.
2001 'Dynamics Boundaries of the Firm: Are Firms Better Off Being Vertically Integrated in the Face of Technological Change?' *Academy of Management Journal*, 44, 6, pp. 1211-1228.

Argyres, N. S.
1995 'Technology Strategy, Governance Structure and Interdivisional Coordination', *Journal of Economic Behavior and Organization*, 28, pp. 337-358

Balakrishnan, S. and B. Wernerfelt
1986 'Technical Change, Competition and Vertical Integration', *Strategic Management Journal*, 7, pp. 347-359.

Balassa, B.
1965 'Trade Liberalisation and 'Revealed' Comparative Advantage', *The Manchester School of Economics and Social Studies*, 32, pp. 99-123.

Brusoni, S.
2003 'Authority in the Age of Modularity', SPRU Electronic Working Paper # 101, University of Sussex, Falmer, UK.

Brusoni, S., A. Prencipe, and K. Pavitt
2001 'Knowledge Specialisation, Organizational Coupling, and the Boundaries of the Firm: Why Do Firms Know More Than They Make?', *Administrative Science Quarterly*, 46, 4, pp. 597-621.

Cantwell, J.
1989 *Technological Innovation and Multinational Corporations*, Oxford: Blackwell.

Cantwell, J.
1991 'Historical Trends in International Patterns of Technological Innovation', in Foreman-Peck, J., *New Perspectives on the Late Victorian Economy*, Cambridge: Cambridge University Press.

Cantwell, J.
1993 'Corporate Technological Specialisation in International Industries', in Casson, M. and Creedy, J., *Industrial Concentration and Economic Inequality*, Cheltenham: Edward Elgar.

Chesbrough, H., and D. Teece
1996 'When is Virtual Virtuous: Organizing for Innovation', *Harvard Business Revi*ew, Jan/Feb, pp. 65-74.

Chesbrough, H.
2003 'The Dynamics of Systems Integration in the Hard Disk Drive Industry', in Prencipe, A. Davies, A., and Hobday, M. *The Business of Systems Integration*, Oxford: Oxford University Press.

Coase, R.
1937 'The Nature of the Firm', *Economica*, 4, pp. 386-405.

Eisenhardt, K. M.

1989 ‘Building Theories from Case Study Research’, *Academy of Management Review*, 14, 4, pp. 532-550.

Geuna, A
2000 *The Economics Of Knowledge Production*, Cheltenham: Edward Elgar

Granstrand, O., P. Patel, and K. Pavitt
1997 ‘Multitechnology Corporations: Why they have ‘Distributed’ rather than ‘Distinctive Core’ Capabilities’, *California Management Review*, 39, 4, pp. 8-25.

Grant, R.
1996 ‘Toward a Knowledge-Based Theory of the Firm’, *Strategic Management Journal*, 17, pp. 109-122.

Harrigan, K. R.
1984 ‘Formulating Vertical Integration Strategies’, *Academy of Management Review*, 9, pp. 638-652.

Harrigan, K. R.
1985 ‘Strategies for Intrafirm Transfers and Outside Sourcing’, *Academy of Management Journal*, 28, pp. 914-925.

Henderson R. M., and K. B. Clark
1990 ‘Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms’, *Administrative Science Quarterly*, 35, pp. 9-30.

Jacobidies, M. G.
2002 ‘Where do Intermediate Markets Come From?’ Paper presented at the Academy of Management Meeting, Denver, Colorado.

Jane’s Aero Engines, 1996, 1997.

Kogut, B.
2000 ‘The Network as Knowledge: Generative Rules and the Emergence of Structure’, *Strategic Management Journal*, 21, pp. 405-425.

Laursen, K.
1998 ‘A Neo-Schumpeterian Perspective on the Determinants and Effect of International Specialisation,’ Unpublished PhD thesis, Aalborg University, Denmark.

Laursen, K.
2000 *Trade Specialisation, Technology and Economic Growth: Theory and Evidence from Advanced Countries*, Cheltenham: Edward Elgar.

Lee, T. W.
1999 *Using Qualitative Methods in Organizational Research*, London: Sage Publications.

Liebeskind, J.
1996 ‘Knowledge, Strategy, and the Theory of the Firm,’ *Strategic Management Journal*, 17, pp. 93-108

Liker, J. K., R. R. Kamath, S. Nazli Wasti, and M. Nagamachi
1996 'Supplier Involvement in Automotive Component Design: Are there Really Large US Japanese Differences?', *Research Policy*, 25, pp. 59-89.

Nelson, R. R.
1991 'Why Do Firms Differ, and How Does it Matter?', *Strategic Management Journal*, 12, 6, pp. 61-74.

Nelson, R. R., and S. Winter
1982 *An Evolutionary Theory of Economic Change*. Cambridge, MA: Belknap Press of Harvard University.

Patel, P. and K. Pavitt
1997 'The Technological Competencies of the World's Largest Firms: Complex and Path-Dependent, but not much Variety', *Research Policy*, 26, pp. 141-156.

Penrose, E.
1959 *The Theory of the Growth of the Firm*, London: Basil Blackwell.

Pisano, G.
1997 *The Development Factory: Unlocking the Potential of Process Innovation.* Cambridge, MA: Harvard Business School Press.

Prencipe, A.
2000 'Breadth and Depth of Technological Capabilities in Complex Product Systems: The Case of the Aircraft Engine Control System', *Research Policy*, 2000, 29, pp. 895-911.

Sako M.
2003 'Modules in Design, Production and Use: Implications for the Global Automotive Industry', in Prencipe, A., Davies, A., and Hobday, M. *The Business of Systems Integration*, Oxford: Oxford University Press.

Sanchez R., and J. T. Mahoney
1996 'Modularity, Flexibility, and Knowledge Management in Product and Organization Design.' *Strategic Management Journal*, 17 (Winter Special Issue), pp. 63-76.

Sapolsky, H. M.
1972 *The Polaris System Development: Bureaucratic and Programmatic Success in Government*, Cambridge, Massachusetts: Harvard University Press.

Scherer, F. M.
1988 'The Propensity to Patent', *International Journal of Industrial Organization*, 1, pp. 107-128.

Soete, L. L. G.
1981 'A General Test of the Technological Gap Trade Theory', *Weltwirtschaftliches Archiv*, 117, pp. 638-666.

Takeishi, A.
2002 'Knowledge Partitioning in the Interfirm Division of Labor: The Case of Automotive Product Development', *Organization Science* 13, 3, pp. 321-338.

Teece, D. J.
1996 ‘Firm Organization, Industrial Structure, and Technological Innovation’, *Journal of Economic Behavior &Organization*, 31, 2, pp. 193-224.

Trochim, W.
1989 ‘Outcome Pattern Matching and Program Theory’, *Evaluation and Program Planning*, 12, pp. 355-366 in Yin (1994), *op. cit.*

Tushman, M. L, and P. Anderson
1986 ‘Technological Discontinuities and Organizational Environments’, *Administrative Science Quarterly*, 31, pp. 439-465.

Williamson, O.
1975 *Markets and Hierarchies: Analysis and Antitrust Implications*, New York: The Free Press.

Williamson, O.
1987 *The Economic of Institutions of Capitalism*, New York: The Free Press.

Wyatt, S., Bertin, G. and Pavitt, K.
1988 ‘Patents and Multinational Corporations: Results from Questionnaire’, *World Patent Information*, 7, 3, pp.196-212.

Yin, R. K.
1994 *Case Study Research: Design and Methods*, London and New Delhi: Sage Publications.

Appendix A

Questionnaire outline

1. How is R&D organized (i.e.: corporate lab, division lab) in terms of mission(s)?
2. Could you give a hint of your R&D project selection mechanisms (i.e.: mainly financial, long-term view)?
3. Is your technology strategy independent of your corporate strategy?
4. What are the relevant issues when you decide to 'make or buy' a component?
5. Do you make a distinction between outsourcing of components and outsourcing of technologies?
6. Does your company have any R&D project(s) dealing with outsourced components? If so, what kind of research is carried out?
7. If so, would you say that such R&D activity is carried out to be an 'intelligent customer' on outsourced components?
8. In your opinion, where does the nature of system integration lie (at the very technical level):
9. Which kind of knowledge do you need to integrate the systems?
10. Has your design strategy changed in the last ten years? In other words, has the percentage of in-house design increased/decreased in the last ten years? Has your manufacturing strategy changed in the last ten years? In other words, has the percentage of in-house manufacturing increased/decreased in the last ten years?
11. Has your company recently (1980-1995) acquired any component suppliers? If so, what was the acquisition rationale? (Please provide a list of relevant acquisitions)
12. Has your company recently (1980-1995) sold any component suppliers (and/or divisions)? If so, what was the divestment rationale? (Please provide a list)
13. Does your company have any cooperative R&D programs with suppliers/customers? If so, could you explain the nature of such agreements and provide a list of them according to the technological areas?
14. Does your company have any cooperative R&D programs with Universities? If so, could you provide a list of them according to the technological areas?
15. How important to the progress of your unit's technological base was publicly available funded research, over the past ten years?
16. Which category makes the largest contribution to your business?