Knowledge Specialization, Organizational Coupling, and the Boundaries of the Firm: Why Do Firms Know More Than They Make?

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This paper uses an analysis of developments in aircraft engine control systems to explore the implications of specialization in knowledge production for the organization and the boundaries of the firm. We argue that the definition of boundaries of the firm in terms of the activities performed in house does not take into account that decisions to outsource production and other functions are different from decisions to outsource technological knowledge. We show that multitechnology firms need to have knowledge in excess of what they need for what they make, to cope with imbalances caused by uneven rates of development in the technologies on which they rely and with unpredictable product-level interdependencies. By knowing more, multitechnology firms can coordinate loosely coupled networks of suppliers of equipment, components, and specialized knowledge and maintain a capability for systems integration. Networks enable them to benefit from the advantages of both integration and specialization. Examples from other industries extend to other contexts the model we develop.●

Since the Industrial Revolution, the production of useful knowledge, like the production of artifacts, has become increasingly specialized and professionalized, with the continuous emergence of new and useful disciplines and subdisciplines. Knowledge specialization has profound implications for the evolution of firms' cognitive and coordination mechanisms and the relationship between firms' production and knowledge boundaries. As the number of disciplines for the design, development, and manufacturing of products increases, firms need to rely on specialized suppliers of equipment as well as knowledge, to complement their in-house research and development (R&D) efforts. It is therefore important to understand why some disciplines and components are developed and produced in house and why others are contracted out. This paper analyzes the reasons why firms maintain technological capabilities in a number of fields wider than those in which they decide to produce, and it explores the implications for firms' boundaries and vertical integration decisions. Defining the boundaries of the firm in terms of activities performed in house does not take into account that decisions to outsource production and other functions are different from those to outsource technological knowledge. Traditional explanations of firms' boundaries, particularly those that rely on transaction costs analysis, therefore, provide only a partial explanation.

To analyze the nature of the boundaries of the firm, we focus on the linkages among firms that interact to develop, design, and manufacture multitechnology products. Multitechnology products are artifacts made up of components and embody a number of technologies. Components are physically distinct portions of the product that carry out specific functions and are linked to each other through a set of interfaces defined by the product architecture (Henderson and Clark, 1990). Technologies are understood as the bodies of knowledge, or understanding and practice, that underpin product design and manufacturing (Pavitt, 1998).

Organization in this context refers to the network of firms that cooperate to design the whole product, manufacture its

0001-8392/01/4604-0597/$3.00.

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The first two authors are to be considered joint first authors, with names reported in alphabetical order. The research for this paper was done at SPRU—Science and Technology Policy Research—as part of the research program on Complex Product Systems (CoPS) funded by the British Economic and Social Research Council (ESRC). The authors gratefully acknowledge funding from the European Commission, Marie Curie Fellowships (grant no. ERBFMBICT9725490) and British Engineering and Physical Sciences Research Council (EPSRC). In addition to comments from Reed Nelson and three anonymous *ASQ* referees, we have greatly benefited from comments on earlier drafts from Ashish Arora, Hank Chesbrough, Ludo Dibiaggio, Roberto Fontana, Alfonso Gambardella, Mike Hobday, Robin Mansell, and Ed Steinmueller.

components, assemble, and market it. In studying the relationships between these firms, we rely on the concept of coupling (Orton and Weick, 1990) to describe how two or more firms interact with each other and how change in one firm within the network affects another. Building on the case of the development of control systems for aircraft engines over the past thirty years, we develop a theoretical framework that attempts to explain the differences and relationship between firms' production and knowledge boundaries.

MULTICOMPONENT, MULTITECHNOLOGY PRODUCTS AND THE BOUNDARIES OF THE FIRM

The notion that there are different types of innovation that call for different organizational forms was highlighted by Henderson and Clark (1990). Besides the traditional distinction between radical and incremental innovations, they introduced the notion of modular and architectural innovations. A modular innovation is a change in the core design concept of a component that does not affect its relationships with the others. 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. They argued that the product's architecture defines key intrafirm functional relationships, information processing capabilities, communication channels, and information filters and that an architectural innovation therefore represents a dangerous challenge for incumbent firms.

Henderson and Clark (1990: 10) focused their analysis on the case in which the product is "designed, engineered, and manufactured by a single product-development organization." Empirical evidence, however, showed that the design, engineering, and manufacturing of products is frequently carried out by networks of specialized designers, equipment suppliers, and manufacturers (von Hippel, 1987; Kogut, 2000). On more theoretical grounds, Richardson (1972: 895) argued, "Firms are not islands but are linked together in patterns of co-operation and affiliation. Planned co-ordination does not stop at the boundaries of the individual firm but can be effected through co-operation between firms."

The increasing specialization of useful knowledge for design, engineering, and manufacturing of products makes it difficult for firms to rely entirely on in-house learning processes. Wang and von Tunzelmann (2000) stressed that the range of disciplines relevant to firms' innovative processes is expanding in both breadth, i.e., the number of relevant disciplines increases, and depth, i.e., their sophistication and specialization increase. The emergence of multitechnology firms that deliver increasingly complex products would not be a cause for analytical concern if specific bodies of technological knowledge could be mapped tidily on to well-identified components and subsystems, but this is not found to be the case. In a number of sectors, technologies and products have been shown to follow interconnected, yet different, dynamics.

More precisely, the knowledge boundaries of firms stretch beyond their production boundaries, and the evolution of their knowledge and product domains unfolds according to different principles. Prencipe (1997) found that aircraft engine manufacturers retain technological knowledge about components whose production is fully outsourced. Gambardella and Torrisi (1998) showed that in the electronics industry, firms are narrowing the range of products they offer, while extending the range of technologies on which they rely. Von Tunzelmann (1998) discussed similar findings in the food industry. Brusoni and Prencipe (2001) compared the case of the aircraft engine with mature chemical engineering design and construction activities and reached similar conclusions. More generally, Granstrand, Patel, and Pavitt (1997) found that large firms are more diversified in the technologies that they master than the products that they make and that their technological diversity has been increasing while they have typically been narrowing their product range.

The gap between firms' production and knowledge boundaries may be the outcome of their efforts to reconcile apparently conflicting objectives. On the one hand, firms aim to exploit flexibility and to cut costs by outsourcing the production and detailed design of modular components and subsystems, i.e., they should buy. On the other hand, firms' competitive positions may depend on the capability to introduce radical product and component innovations by building on in-house technological capabilities, i.e., they should make. Traditional explanations of firms' boundaries are ill equipped to explain the paradox pinpointed above: firms invest in broadening their knowledge bases while narrowing down their manufacturing bases.

Traditional Explanations of the Boundaries of the Firm: Transaction Costs and Modularity

In Williamson's (1975, 1985) transactions cost approach, knowledge appears as a production input, the characteristics of which are likely to lead to market failures. Empirical research consistently points to two key problems associated with knowledge-intensive activities. First, the partially tacit nature of knowledge, embodied in people and organizational routines, makes it highly specific and difficult to transfer (Nelson and Winter, 1982). Monteverde and Teece (1982: 209) argued that components that are specific to a company and that exhibit systemic effects are most likely to be manufactured in house, since their production process is built on specialized and non-patentable know-how. In addition, Mowery (1983) showed that although U.S. firms funded contract R&D for routine analytical tests, strategically important fundamental research and product development was kept in house. The nature of the output of R&D activity leads to another problem associated with knowledge-intensive activity, namely, appropriating its benefits. For instance, Pisano (1990) analyzed the evolving governance structures of biotechnology R&D and argued that, despite the advantages of collaboration, both specialized biotechnology firms and established pharmaceutical firms face transactional problems due to the weak conditions for appropriating knowledge resulting from their R&D. These problems led them toward increasing vertical integration.

Empirical and theoretical studies on modularity have also attempted to explain the organizational implications of technological change. These studies follow a logic consistent with previous work inspired by transaction costs. Modularity is a product design strategy aimed at enhancing the interchangeability of components within a given architecture. Ulrich (1995) defined a modular architecture as a scheme that defines a one-to-one mapping between physical components and functional elements. Components' interfaces are standardized and interdependencies among components are decoupled, in the sense that changes in the key functional concept of each component do not affect the behavior of others.

Modular strategies have important implications for the definition of the boundaries of and the relationships across organizational units dedicated to the development of a product. Sanchez and Mahoney (1996) argued that a modular product would make possible the adoption of a modular organization, whereby each module would be developed by a dedicated organizational unit, which would also embody all the knowledge relevant to its development and manufacturing activities. Arora and Gambardella (1994) pushed this line of reasoning further, arguing that the increasing availability of general and abstract knowledge modules would decrease the asset specificity attached to knowledge-intensive transactions, thus extending the use of markets for knowledge, as opposed to hierarchies.

None of these authors recognized the gap between what firms make and what they know. They assumed that what firms make is a good proxy for what firms know and thus focused their analysis on the two extreme cases of decentralized markets vs. integrated hierarchies. These approaches do not fully describe or explain the organizational implications of multitechnology, multicomponent products, as we shall show in the following discussion of the long-term evolution of the aircraft engine control systems.

Technological Change in the Aircraft Engine Control System

We chose to study the development of aircraft engine control systems for three reasons. The first relates to the larger product that the control system is part of, namely, the aircraft engine. Aircraft engines are multitechnology, multicomponent products. Components differ in functions and criticality and exhibit patterns of interdependencies of varying complexity. Components also rely on different and often distant technological fields that advance at different, and not necessarily consistent, rates of development; to name but a few, thermodynamics, aerodynamics, fluid dynamics, tribology, heat transfer, combustion, structures, materials, manufacturing processes, instrumentation, and controls (Mattingly, Heiser, and Daley, 1987). The multitechnology, multicomponent nature of the aircraft engine enables the analysis of the boundaries of firms with respect to their network of suppliers.

Second, over the last thirty years, the engine control system has been characterized by a radical shift in its underlying technologies: from hydromechanics to digital electronics. The shift was partly due to the uneven rate of change in the technologies underlying the control system (i.e., hydromechanics) and those underlying the engine power system (i.e., gas turbine). The unevenness in the rates of change caused what Rosenberg (1976) called a technical imbalance. This happens when the potential for one part of the system to improve its performance is so considerable, due to improved understanding of its underlying technologies, that it requires attention to be devoted to complementary improvements elsewhere in the system. Examples include the complementary improvements in spinning and weaving in the nineteenth century textile industry (Landes, 1969) and the development of numeric control technologies in the machine tool industry (Mazzoleni, 1999).

Third, as a result of the high rate of technological advance of digital electronics, control system performances have improved dramatically, so that the control system has become a pivotal part of the aircraft engine, generating a new set of imbalances at the level of the engine system. We explore the extent to which aircraft engine manufacturers have adjusted their knowledge and production boundaries over time to embody changing component technologies in the control system, while maintaining high standards of technological safety and reliability.

METHOD

The paper draws on data collected during a four-year field study of the aircraft engine control system industry. The study is part of a larger research project designed to explore the distinction between the knowledge and production boundaries of firms that develop complex products like aircraft engines (Prencipe, 2002). This study relies on both qualitative and quantitative evidence, which helps establish solid construct validity (Eisenhardt, 1989; Yin, 1994). Primary sources of qualitative data included on-site interviews with representatives of the world's three largest engine manufacturers and four control system suppliers. 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 percent of the world market. The names of the firms have been disguised for confidentiality reasons.

A total of twenty in-depth, semi-structured interviews, lasting about two hours, were conducted with senior technical managers and control system designers of both aircraft engine manufacturers and control system suppliers. The specific aim was to assess the strength and reveal the determinants of the relationship between aircraft engine makers and their suppliers. Interviewees were asked to comment on the managerial implications (in terms of technological capabilities to be developed and organizational change needed) resulting from the introduction of technological innovations in the control system. To validate our analysis, a draft of the empirical part of the paper was circulated to the key individuals interviewed, and the accuracy of the account was discussed over the phone in supplementary interviews.

The quantitative analysis is based on U.S. patent data, which were collected using the U.S. Patent CD-ROM and double-checked with the legal offices within each company. We relied on the U.S. patent classes' definitions and the help of two U.S. Patent Office primary examiners to identify those patents related to control system technologies. By using patent data, we aimed at integrating the qualitative analysis of the emergence of alternative organizational settings with the quantitative analysis of the development and maintenance of in-house technological capabilities.

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, however, we compare companies' patenting shares within the same sector. We used qualitative data collected via on-site interviews to overcome limitations of the patent analysis, such as the measurement of software technology. Qualitative data were used to validate the accuracy of the results and meaning of the patent analysis and to write case histories of the technological evolution of the aircraft engine control system.

THE EVOLUTION OF AIRCRAFT ENGINE CONTROL SYSTEMS

In the 1950s, aircraft engine control systems were based on hydromechanical technologies and were complex artifacts. They encompassed a large number of components and subcomponents, and they were application-specific, such that a change in the design of the engine required a change in the design of the control system. Hydromechanical control systems reached a technological ceiling in a relatively short time. The maturity of the technology enabled engineers to understand, articulate, and modularize the interfaces between the engine and the hydromechanical control system. Furthermore, performance improvements derived primarily from operational experience rather than from scientific or technological breakthroughs (Prencipe, 2000). In the mature stage of development reached in the 1970s, hydromechanical control systems were characterized by a relatively low rate of technological change and increasingly predictable interdependencies with the other components.

Although hydromechanical control systems had achieved relatively high reliability, they displayed limitations. Higher-thrust engines that were being developed during the 1970s were characterized by a larger number of parameters that needed accurate measurement and computation. In particular, the increasing bypass ratio (i.e., the ratio of mass flow through the fan or bypass duct to that through the core) of the newly developed engines posed several problems for the calculation and control of thrust during engine operation. To avoid over-boost and over-temperature, more frequent adjustments of the power lever were required (Prencipe, 2000). Traditional hydromechanical control systems could not manage this problem.

The complexity of thrust calculations, the high accuracy and quick-response time required, and the fact that most parameters (turbine temperature, fan speed, altitude) were available in electronic form therefore rendered digital electronics more suitable for control systems (Flanders, 1974; Griffiths and Powell, 1974). 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. In addition, digital control systems' potentialities created new sets of technological imbalances between the control system and the engine power system.

Although digital control systems interacted with, in fact, controlled, a higher and enlarging number of engine components, these interdependencies were governed by the so-called interface software. Due to this software component, digital control systems were not application-specific, and hardware and software modules could be reused in different applications. Digital control systems therefore exhibited predictable product systemic interdependencies, since such interdependencies were managed by the interface software (Prencipe, 2000).

We analyze the paths of adjustments of the knowledge and production boundaries of the three firms under examination, as well as the changes in their relationships with their suppliers, with respect to the hydromechanical and digital electronics trajectories. The analysis focuses on three key elements of the story. The first two are the links between the evolution of the hydromechanical and digital electronic trajectories and the related organizations. The third is the coordination mechanisms that enabled aircraft engine makers to manage the technological and organizational interfaces with their suppliers in a fast-changing environment. While the analysis of the first and second elements is largely based on interviews, the third one is analyzed using both patent data and interviews.

Evolving Networks: The Hydromechanical Trajectory

Although they competed with similar products in similar markets, the three engine manufacturers initially adopted different technology and organizational strategies in the design and production of engine control systems. Company A and Company B relied on their own captive suppliers for the development of this subsystem. In contrast, Company C always relied on external suppliers. Interviewees stated that the top managers of Company C considered their main business to be the development of aircraft engines and their main capabilities in disciplines such as aerodynamics, thermodynamics, and combustion, not in control systems and, therefore, not in hydromechanical, or later, in digital electronics. The fact that firms' responses may differ despite similar technological or market conditions is consistent with the evolutionary approach (Nelson, 1991).

The technological and ensuing functional shift that characterized the control system led the three engine manufacturers to adjust their knowledge, production, and organizational boundaries. In the 1970s, when hydromechanics was the leading technology, Company A was characterized by an integrated organization, since it relied on an internal supplier for the design and production of control systems. As the product interdependencies characterizing hydromechanical control systems became well understood and articulated, it moved away from the integrated solution via the outsourcing of design and manufacturing activities of hydromechanical components. Company B maintained its exclusive engine control system supplier throughout the life cycle of the hydromechanical trajectory. Both Company B and the engine control system supplier operated as independent divisions of a larger company. Although their relationship was defined as a typical contractor-subcontractor relationship, the control systems for Company B's engines were designed and developed jointly with this internal supplier, and the development costs were shared. In the 1970s, when hydromechanics was the leading technology, Company C did not have any in-house control system supplier. It initially relied on a relatively strong relationship with a supplier. This relationship became weaker when the technology stabilized and the product systemic interdependencies were more fully understood.

Evolving Networks: The Digital Electronics Trajectory

In the 1980s, digital electronics emerged as the alternative and better technology. As the new technology emerged, Company A pursued a policy of in-house development and design of the digital components associated with it. Thus, it was initially characterized by an integrated structure. Subsequently, it started moving away from that structure, toward the eventual sale of its internal supplier in 1996. As a result of this move, Company A started outsourcing the production of control systems components to its former internal suppliers 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 tight control of the development and commercialization activities of control systems. According to the supplier's marketing manager, "The relationship [between aircraft engine maker and control system supplier] was exclusive by tradition in the early years and reinforced in the early 1980s when we started the development of digital electronic engine controls." Moreover, the possibility of selling engine controls to competitors (and in particular to Company C) was ruled out. Company B was characterized by a quasi-integrated structure. The peculiarity of Company B's policy reflected the importance of its own control system supplier, which had grown as big as the aircraft engine maker division, given its heavy involvement with the defense business. The strategic role it came to play in Company B's overall profitability led the management to reject any possible loosening of the degree of integration with the control system division.

Unlike its competitors, Company C always maintained arm's-length market relationships with its suppliers and, therefore, took longer than its more integrated rivals to identify the developments of digital electronics. Only in the late 1980s, following the problems it faced in the integration of this new fast-moving technology, did Company C start developing capabilities in digital technologies through in-house investments in digital electronics as well as through links with external suppliers and universities. Interviewees in Company C confirmed that it had been harder, in terms of resources to be invested, for them to reach adequate quality and reliability in their control systems. Although they eventually caught up with competitors in terms of technical reliability, they had to spend more resources than Companies A and B to develop and integrate control systems satisfactorily (Prencipe, 2000).

The In-house Technological Capabilities of the Aircraft Engine Makers

While the relationship between engine makers and their suppliers of control systems changed in terms of division of labor, the division of knowledge that underpins engine makers' organizational adjustments also evolved as digital electronics became the dominant technology. We used U.S. patent statistics as a proxy measure of these capabilities. Table 1 reports on the rate of growth of the control-systems-related patents as compared with the overall rate of growth of the companies' patents. This comparison enabled an assessment of the dynamics of changes in the relative importance of control systems technologies in each of the firms analyzed. For completeness, table 1 also reports on the patent shares related to control systems technologies, both hydromechanical and digital, in the three firms examined. Patent shares were calculated over the overall number of patents granted to each firm between 1977 and 1996. Patent shares provided an approximate indication of the importance of a firm's capabilities in control system technologies relative to a firm's overall technological capabilities.

Table 1 shows that despite being characterized by different and changing ownership structures, the companies studied all made similar and significant investments in control sys-

Table 1

Patent Shares and Rate of Growth (% over Previous Period) of Control-System-related Technologies*

Company A	1977–81	1982–86	1987–91	1992–96
Share of control-systems-related patents over total patents	11.4	12.7	7.2	8.6
Growth rate (%) of control systems patents		–30	60	150
Growth rate (%) of overall patents		–40	170	110
Company B				
Share of control-systems-related patents over total patents	10.6	12.3	16.7	9.4
Growth rate (%) of control systems patents		50	80	–40
Growth rate (%) of overall patents		30	30	10
Company C				
Share of control-systems-related patents over total patents	5.7	7.4	11.3	9.9
Growth rate (%) of control systems patents		60	40	–4
Growth rate (%) of overall patents		30	–10	10

* Adapted from Prencipe (2000).

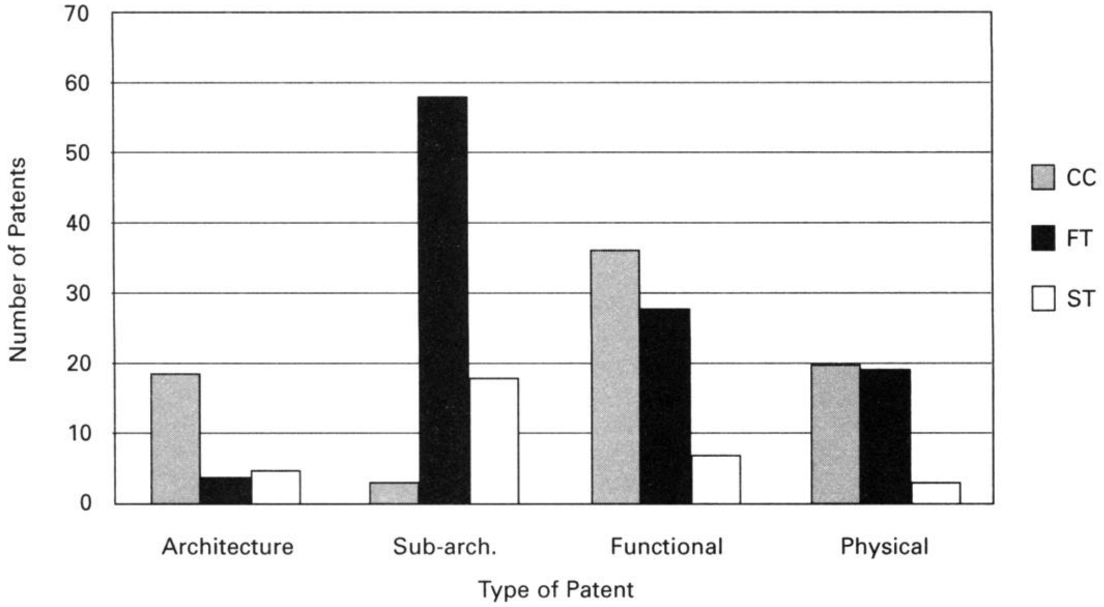
tems knowledge. The case of Company C is particularly interesting. Although it did not design or produce control systems, Company C exhibited a sharp rise in the rate of growth throughout the first two periods and a decrease in the last. We interpret the drop in the last period as the effect of the emergence of an industry-dominant design. Extensive interviews confirmed that this pattern reflects Company C's efforts to develop technological capabilities to coordinate proactively 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.

Thus, while it was specialized in terms of division of labor, Company C showed an increasingly diversified pattern of knowledge. This discrepancy can be further scrutinized by comparing its technological profile with those of the world's two largest independent suppliers of aircraft engine control systems, one first-tier and one second-tier. The case of Company C is revealing: it had never designed or manufactured an engine control system, and it had previously regarded its underlying technologies as outside the company's core capabilities.

To construct the firms' technological profiles, we grouped the patents of the companies according to four main categories, namely, architecture, sub-architecture, functional, and physical. These four groups enable an in-depth analysis of the extent of specialization in technological capabilities between engine manufacturers and suppliers. Architecture patents are those whose abstract describes how components are arranged in a system. Sub-architecture patents are those whose abstract describes how components are arranged in a subsystem. If the main content of the patent abstract describes functional behavior of a system, i.e., what the system does, we labeled patents as functional. Physical patents are those whose abstract concerns the physical description of an item or a subsystem, i.e., what the system looks like. The breakdown into architecture, sub-architecture, functional, and physical groups was made by the head of engine control system of one of the world's largest engine manufacturers on the basis of the patent abstracts available on the Web site of the U.S. Patent Office.

Figure 1 reports the results of our analysis. Although Company C had the largest number of architectural patents, it did not have the largest number across all fields. Suppliers also played an active, innovative role, especially in the sub-architectural, functional, and physical fields. At the same time, Company C's patenting did not focus solely on the architecture of the control system; it was also granted other patents, mainly in the physical and functional categories. Thus, although it did not design or manufacture any components of the engine control system, Company C developed and maintained an understanding of the functioning and characteristics of the units in the engine control system. Such understanding was a necessary condition to integrate the different components together and within the engine system. The increase

Figure 1. Comparison of the control systems patenting activity of Company C (CC), a first-tier supplier (FT), and a second-tier one (ST) between 1977 and 1996 (source: Prencipe, 2000).



in Company C's share of patents in control systems, and their spread over the four categories analyzed, also showed that the company developed capabilities to specify and test externally produced components, as well as to identify and coordinate the integration of new technological developments.

Why the Division of Labor and the Division of Knowledge Can be Different

This case study of the aircraft engine control system has illustrated a number of points raised by earlier empirical research on the boundaries of the firm. The evolution of the hydromechanical and digital electronics trajectories played a fundamental role in explaining firms' outsourcing decisions related to both knowledge and production. During the early stages of major product developments, interdependencies among components were high and poorly understood. Organizational integration was therefore necessary to achieve coordination. This result is fully consistent with Williamson's (1971: 120–121) analysis: actual and potential interdependencies across components may cause "the costs of negotiations and the time required to bring the system into adjustment by exclusive reliance on market (price) signals" to be greater than the costs and time required should "successive stages [be] integrated."

As the technology matured, interdependencies became better understood and easier to predict and, thus, specialization prevailed. Following Williamson, Teece (1976) argued that the degree of integration between component suppliers and users depended inversely on the degree of predictability of interdependencies across components. Interdependencies across components are predictable when a change in the design of one component entails a well-understood change in the design of other components, and vice versa. Teece (1976: 13) also argued that, in the presence of contingencies that cannot be perfectly predicted, "co-ordinated activity is required to secure agreement about the estimates that will be used as a basis for action. Vertical integration facilitates such co-ordination." Other elements of our story, however, do not fit this framework.

In particular, the case study showed that when digital electronics stabilized, aircraft engine makers outsourced the design and manufacturing of an increasing number of components but maintained in-house technological capabilities related to the outsourced components. The key points are that decisions to outsource technological knowledge differ from decisions to outsource component production and that uneven rates of change in component technologies are an important determinant of knowledge outsourcing. If fast-changing technological fields (e.g., digital electronics) displace slowly changing fields (e.g., hydromechanics), firms must develop and keep in house the technological knowledge to accommodate changes in one field that may have cascade effects on others. In this respect, the case of Company C is revealing. Our interview data underlined the fact that the efforts that Company C undertook to master the new trajectory, and thus develop in-house capabilities, did not affect its policy to rely on external suppliers for the detailed engineering and production of individual components. To cope with such a rate of change and to monitor continuously the evolving trajectory, Company C also developed and maintained in-house technological capabilities via collaborative agreements with external sources of components and technologies of control systems (suppliers and universities). This is a key point that is not captured by analyses informed by the transaction cost economic framework proposed by Williamson (e.g., Monteverde and Teece, 1982) or by the modularity framework (e.g., Sanchez and Mahoney, 1996).

The modularity literature does not capture the fact that, despite the increasing predictability and modularization of the interdependencies between the digital control system and the rest of the aircraft engine, specialization in the activity domain was not accompanied by specialization in the knowledge domain: the division of labor did not match the division of knowledge. In contrast, scholars of technological change have stressed that different technological fields are characterized by different degrees of innovative opportunity, e.g., microelectronics and biotechnology vs. civil engineering and hydromechanics (Malerba and Orsenigo, 1996). As a consequence, multitechnology products are likely to generate situations characterized by uneven rates of development in the component technologies on which they rely. When this happens, organizations such as those we studied need to develop coordinating mechanisms to accommodate changes in fields that cause imbalances and have cascade effects on others.

The idea of imbalances builds on research on complex artifacts. In his study on electric power generation, Hughes (1992) developed the notion of a "salient." It can be explained using a military metaphor. If a division advances deeper and faster than the rest of the front, a salient is created. This is when integration needs to kick in. The military leader will need either to figure out how to push the whole front ahead to catch up with the front-runners or to stop the front-runners and order them to retreat, to avoid them being cut off and killed. If the whole front advanced at the same pace, this problem would not be created. In other words, the salient creates a systemwide performance problem that needs to be accommodated via conscious coordination. Our analysis suggests that, even in the presence of stable (modular) physical interfaces, imbalances may emerge at the technological level.

The case of Company C illustrates the aims of firms that are involved in the design and production of multitechnology, multicomponent products. 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 (Prencipe, 2002). We use this distinction to introduce and discuss the notion of systems integration, a specific coordination mechanism that falls between markets and hierarchies.

There are organizational implications for firms, like those that we have described in aircraft engines, that need to reconcile specialization in the production domain while remaining integrated in the knowledge domain. The key puzzle is the coexistence of elements of specialization and integration at all times. To solve this puzzle, we rely on the notion of organizational coupling and link it to the aims of innovative organizations. Building on the above case study and previous work (Brusoni, 2001), we propose two determinants of the appropriate form of interfirm relationships and their degree of coupling: (1) consistent with transaction cost economics, the degree to which product and component interdependencies can be predicted and (2) unevenness in the relative rates of change of component technologies (i.e., technological imbalances). The combination of these two determinants entails specific organizational requirements that need to be met in order to manage change and innovation successfully.

ORGANIZING FOR INNOVATION: THE CONCEPT OF COUPLING

The aim of innovating organizations developing multitechnology, multicomponent products is twofold. They generate variety by developing specialized bodies of knowledge to foster the process of discovery of novel solutions. They also coordinate dispersed learning processes carried out within different organizations. The generation of variety calls for some degrees of specialization among organizational subunits (e.g., firms, divisions, R&D labs), based on the different scientific and technological disciplines these units master and on the idiosyncratic learning processes and search paths they pursue. The achievement of coordination requires some degrees of integration among organizational subunits to identify and actively manage the relevant technological and organizational interfaces (Lawrence and Lorsch, 1967). Orton and Weick (1990: 205) used the interaction of specialization and integration (which they called distinctiveness and responsiveness, respectively) to determine the extent of coupling across organizational units:

> If there is neither responsiveness nor distinctiveness, the system is not really a system and it can be defined as a noncoupled system. If there is responsiveness without distinctiveness, the system is tightly coupled. If there is distinctiveness without responsiveness, the system is decoupled. If there is both distinctiveness and responsiveness, the system is loosely coupled.

Knowledge specialization per se plays a major role in explaining the emergence of loose coupling. Clark (1983: 16) quoted in Orton and Weick (1990: 206), focused on changes in university structures:

> [A]n academic system works with materials that are increasingly specialized and numerous, knowledge-intensive and knowledge-extensive, with a momentum of autonomy. This characterization applies most strongly to advanced systems, but even the most retarded systems will be based on a half-dozen or more distinct bundles of knowledge that have their own internal logics and an inherent bent toward autonomy.

This description of universities also fits the situation faced by multitechnology firms. The increasing number of highly specialized bodies of knowledge hampers the effectiveness of vertical integration as a coordination mechanism and pushes firms to increase their reliance on a combination of in-house and contract R&D (Langlois, 1992; Granstrand, Patel, and Pavitt, 1997), as well as on externally designed and manufactured components and subsystems. At the same time, the control system case and other previous research illustrate the need for "lean" companies to maintain wide (and widening) knowledge bases.

The usefulness of the concept of loose coupling lies in its capacity to frame, in a unified analytical setting, the study of two important aspects (specialization and integration) of firms developing multicomponent, multitechnology products: loosely coupled organizations exhibit properties of both decoupled and tightly coupled systems. We use the concepts of product systemic interdependencies and technological imbalances to identify the conditions under which "looseness contributes to successful change" (Weick, 1982: 378). We use the case study of the aircraft engine control system to illustrate the conditions under which firms within organizations (i.e., networks) should be loosely coupled among each other in relation to the evolution of technologies and products they develop and market. We also focus on the specific coordination mechanism on which loosely coupled networks rely and which differentiates them from tightly coupled and decoupled networks.

The Case of the Aircraft Engine Control System: Toward a Typology and a Theory

The influences of product systemic interdependencies and technological imbalances on the structure of firms' organizational networks are framed in the two-by-two matrix shown

Figure 2. Determinants of organizational coupling (source: adapted from Brusoni, 2001).

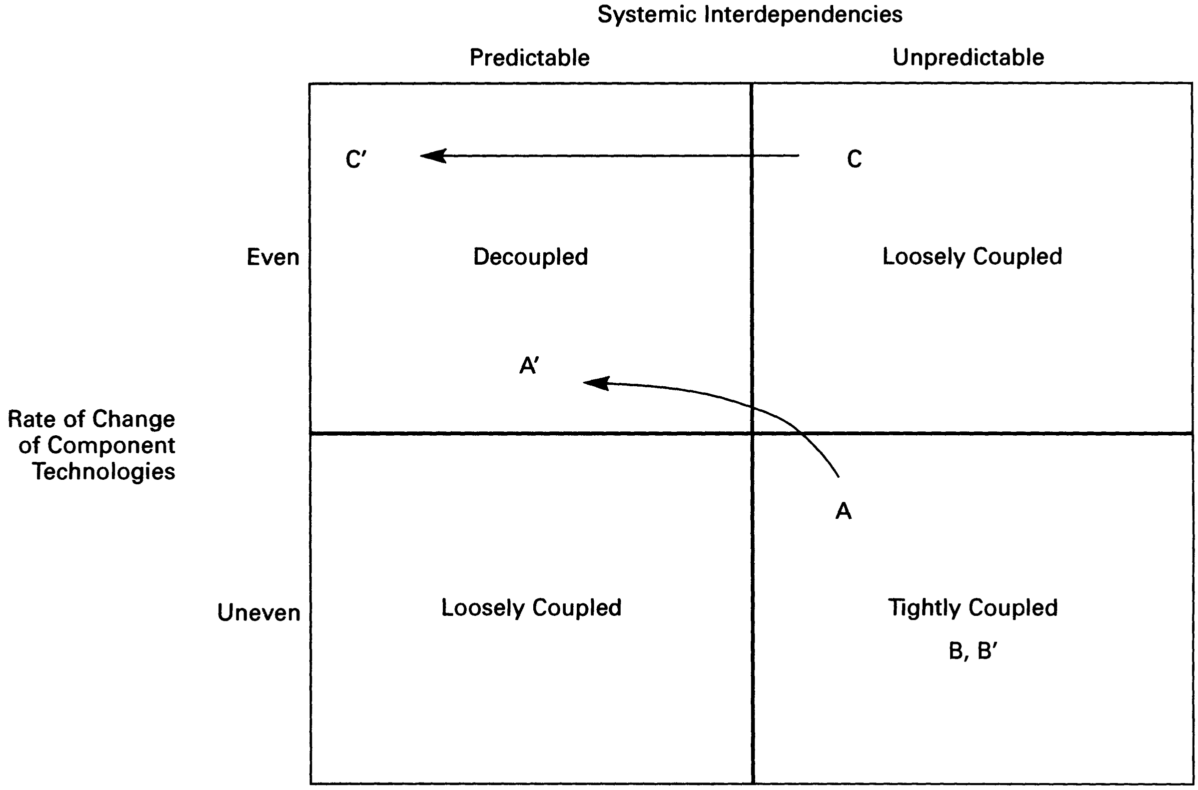
Rate of Change of Component Technologies	Product Interdependencies: Predictable	Product Interdependencies: Unpredictable
Even	*Decoupled* Distinctiveness No Responsiveness Coordination via market mechanisms	*Loosely Coupled* Distinctiveness Responsiveness Coordination via systems integration
Uneven	*Loosely Coupled* Distinctiveness Responsiveness Coordination via systems integration	*Tightly Coupled* Responsiveness No Distinctiveness Coordination via vertical integration

in figure 2. The horizontal dimension of the matrix captures the product-level interdependencies, while the vertical captures the technological-level imbalances. The resulting four quadrants identify three network organizational forms, namely, decoupled, tightly coupled, and loosely coupled. These organizational forms are characterized by distinct interfirm coordination mechanisms, i.e., market, vertical integration, and systems integration.

We illustrate this framework interpreting the adjustment of the knowledge and production boundaries of the three engine manufacturers with respect to their network of suppliers using the analytical categories presented in figure 2. Figure 3 shows the organizational implications of the hydromechanical trajectory. When hydromechanics was the leading technology, Company A was characterized by a tightly coupled organizational network, since it relied on an internal supplier for the design and production of control systems (A in the bottom-right quadrant). As the technology stabilized and product interdependencies became well understood and articulated, Company A moved from a tightly coupled to a decoupled setup via the outsourcing of design and manufacturing activities of hydromechanical components (A′ in the top-left quadrant).

Company B maintained a tightly coupled structure throughout the life cycle of the hydromechanical trajectory (B, B′ in the bottom-right quadrant of figure 3). During the initial stage of the hydromechanical trajectory, Company C had a loosely coupled network structure (top-right quadrant), which progressively became decoupled as the technology stabilized

Figure 3. Determinants of organizational coupling in the hydromechanical trajectory.

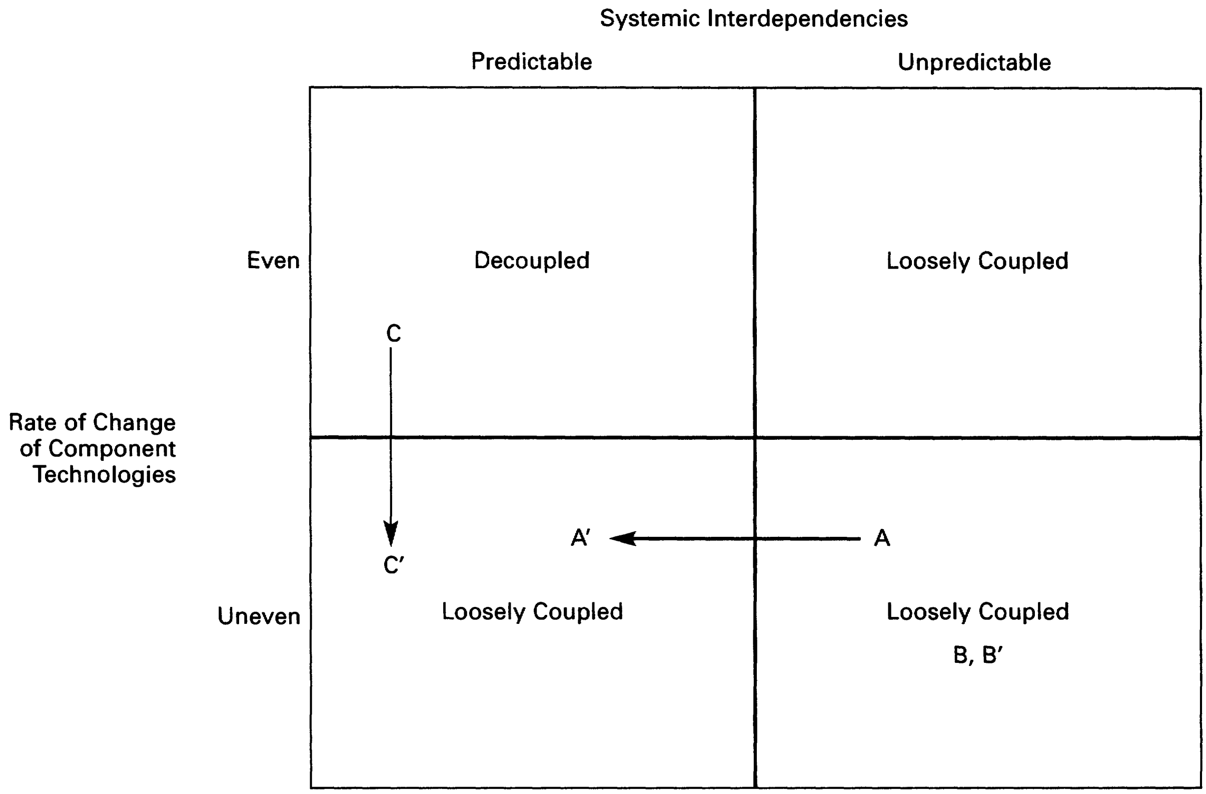


and the system interdependencies were more fully understood (C′ in the top-left quadrant). Unlike Company B, Companies A and C followed similar paths of adjustment in their knowledge and production boundaries. When technology matured and the systemic interdependencies of the product's components became well understood and modular, companies A and C moved toward a decoupled structure via the outsourcing of both design and manufacturing tasks to external suppliers of components and technologies. As said above, the peculiarities of Company B are due to its relatively larger involvement in defense-related development activities.

Figure 4 shows the organizational implications of the digital trajectory. Digital electronics emerged as the alternative technology during the 1980s. At the initial stage of development, systemic interdependencies were high, and the technology moved faster than other components' underlying technologies. Company A initially had a tightly coupled structure but, with the sale of its internal supplier in 1996, moved toward a loosely coupled network structure (A′ in the bottom-left quadrant). It maintained in-house systems knowledge in order to design the architecture of the control system, integrate the components back into the engine, and monitor further development in digital electronics.

Company B continued its policy of tight control in the development and commercialization activities of aircraft engine control systems. It is shown as B, B′ in the bottom-right quadrant in figure 4. Following the introduction of digital electronics and the problems it faced in the integration of this new fast-moving technology, Company C moved toward a

Figure 4. Determinants of organizational coupling in the digital electronics trajectory.



loosely coupled network structure (C′ in the bottom-left quadrant). It started developing in-house systems knowledge through investments in digital electronics as well as links with external suppliers and universities.

The framework proposed above captures well the paths of adjustments of the knowledge and production boundaries of two of the engine manufacturers throughout the technological evolution of the control system. Both Company A and Company C adopted loosely coupled network structures to manage developments in digital electronics technology that was characterized by a faster rate of change than in gas turbine technologies. The unevenness in technological advances of the different fields underlying aircraft engines required some degree of integration at the knowledge level to identify potential novelties in fast-moving technological fields (e.g., digital electronics), understand their implications for the others (e.g., gas turbines), and integrate changes in existing or new product architectures.

Balancing Specialization and Integration: The Role of Systems Integrators

A distinguishing feature of loosely coupled organizations is the presence of systems integrators: firms (such as Companies A and C) that lead and coordinate from a technological and organizational viewpoint the work of suppliers involved in the network. Systems integrator firms outsource detailed design and manufacturing to specialized suppliers while maintaining in-house concept design and systems integration capabilities to coordinate the work (R&D, design, and manufacturing) of suppliers. Systems integration appears, therefore, to be a particular type of coordination mechanism between markets and hierarchies. While markets satisfy the need for distinctiveness, and hierarchies the need for prompt responsiveness, systems integration reconciles them for specific products and technologies. The relationship between systems integrators and their suppliers is governed by contractual arrangements, ranging from the typical arm's-length contractual relationships and cost-sharing agreements to joint ventures and formal alliances. The specific governance structure may vary with the complexity and criticality of the component or activity considered (Prencipe, 2002), as well as with appropriability considerations (Teece, 1986).

The concept of loosely coupled organizations we propose is similar to that of core networks put forward by Robertson and Langlois (1995: 550). Loosely coupled organizations are led by systems integrators. Systems integrators are more than the assemblers that operate within core networks. Systems integration includes the technological and organizational capabilities to integrate changes and improvements in internally and externally designed and produced inputs within an existing product architecture. This dimension of systems integration capabilities is based on Henderson and Clark's (1990: 11) concept of architectural knowledge, i.e., "knowledge about the ways in which the components are integrated and linked together into a coherent whole." But systems integration also has a more dynamic role, namely, maintaining the capabilities required to introduce new product architectures (Prencipe, 2002). In multicomponent, multitechnology products, the periodic introduction of new product architecture requires the coordination of change across a large number of technological fields that may well be developed by an external source. In turn, such coordination requires an all-round knowledgeable firm. The framework we have developed on the basis of our case study can be used to help us understand the evolution of a number of industries besides that of the aircraft engine control system.

Organizational Coupling in Other Industries

The evolution of vertical linkages in the presence of technical change has attracted considerable attention in recent years (Langlois and Robertson, 1992; Davies, 1999; Sako and Murray, 1999; Baldwin and Clark, 2000; Orsenigo, Pammolli, and Riccaboni, 2001). Relying on in-depth case study methodologies, most of these studies have captured specific aspects related to the characteristics of the idiosyncratic product industry studied. We use the framework described in figure 2 to integrate the conclusions of these studies and to develop a more general understanding of the relationship between changes in the division of labor and the division of knowledge through an analysis of organizational coupling in four industries.

The PC industry as an example of decoupled organization. Products characterized by even rates of change among component technologies and predictable interdependencies at the product level are manageable via decoupled organizations coordinated via arm's-length market relationships. This situation is depicted in the top-left quadrant in figure 5, which

Figure 5. The managerial implications of organizational coupling in four industries.

Rate of Change of Component Technologies	Product Interdependencies: Predictable	Product Interdependencies: Unpredictable
Even	Decoupled *PC industry* Outsource design and production. Focused R&D. Coordination via market mechanisms.	Loosely Coupled *Automotive industry* Outsource production and detail engineering. Both contract and in-house R&D. Coordination via systems integration.
Uneven	Loosely Coupled *Hard disk drive industry* Outsource production and detail engineering. Both contract and in-house R&D. Coordination via systems integration.	Tightly Coupled *Mobile phone systems* Design, production and R&D in house. Coordination via vertical integration.

depicts the managerial implications of organizational coupling. This situation reflects the case of modular products that are designed and manufactured within network organizations characterized by the presence of systems-assembler firms that rely on suppliers for the design and manufacturing of components. Within a modular product, each module can be improved within a predefined range of variation without affecting the design of the other modules (Ulrich, 1995).

Specialization (i.e., distinctiveness) within a modular architecture allows each component producer to make experiments and thus increase the pace of innovation as it happens, for instance, in the personal computer (PC) industry (Langlois and Robertson, 1992; Baldwin and Clark, 2000). A modular architecture, built around standardized interfaces, would enable a process of progressive specialization of R&D, production, and marketing activities in such a way that each component (e.g., disk drive, microprocessor, operating system, application software) would define the boundary of a firm whose relationships with the others would be mediated via decentralized market transactions (top-left quadrant of figure 5). Integration (responsiveness) would not require any conscious managerial effort because it would be achieved just by respecting the technological and organizational interfaces defined by the modular architecture.

The telecommunications equipment industry as an example of tightly coupled organization. Products characterized by both component technologies changing at uneven rates and unpredictable interdependencies across components require tightly coupled organizations, in which large, integrated firms maintain in house both the knowledge and the production activities involved in the design and production of their final products and component units. In this setting, coordination is achieved via vertical integration. This situation is depicted in the bottom-right quadrant of figure 5 and fits the case of the telecommunication equipment industry. Davies (1999) studied the evolution of the division of labor between equipment suppliers and network operators in the case of mobile phone systems. Due to the fast rates of change in component technologies, especially software-controlled switching technologies and electronics, and the impact these changes had on the interdependencies across physical components, equipment supplies for mobile phone systems have become the sole trade of integrated firms. Firms like Ericsson, Nokia, and Motorola can design, manufacture, and install the entire range of phone system components: radio base stations, switching centers, and base-station controllers.

Davies (1999) discussed the complex interaction between advances in component technologies and changes in physical equipment. The advantage of a "single vendor solution" lies in the supplier's experience in delivering "a verified system in which all the components work well together, and can be integrated, tested and ready for service more rapidly than is possible in multivendor solutions" (Davies, 1999: 120). This experience is required to fine-tune the phone system to the specific technological, geographical, and legal requirements of the network operator. More specifically, Davies argued that the key advantage of Ericsson, the world leader throughout the 1990s, was its constant involvement in both architectural and component innovations, as well as its efforts to control production costs. In terms of figure 5, through vertical integration and tight coupling, Ericsson achieved technological and organizational responsiveness while minimizing the organizational distinctiveness that may have hampered its competitive position.

Automotive and hard disk drive industries as examples of loose coupling. Loosely coupled organizations are appropriate structures when multitechnology products are characterized either by even rates of advance in underlying technologies and unpredictable product interdependencies (e.g., automotive) or by uneven rates of advance in underlying technologies and predictable product interdependencies (e.g., hard disk drive industry).

The top-right quadrant of figure 5 captures some aspects of the automotive industry. Sako and Murray (1999) 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 "subtle linkage between the body, chassis, engine, and drive-train" (p. 4). Despite having outsourced the design and manufacture of the body, chassis, cockpit, drive-train, and sometimes even the engine, car manufacturers need to maintain the integration capabilities necessary to obtain "a workable automobile" (p. 4). Outsourcing the production of components does not necessarily entail outsourcing the bodies of knowledge employed to specify, design, integrate, manufacture, test, and assemble them.

This case of the automotive industry takes further the insights of Teece (1976) and Williamson (1971) that unexpected contingencies cannot be efficiently managed via repeated short-term contracts and thus require explicit organizational coordination "to secure agreement about the estimates that will be used as a basis for action" (Teece, 1976: 13). What Teece's and Williamson's frameworks did not capture, however, is the maintenance by car makers of these capabilities through systems integration, while they outsource the detailed engineering and manufacturing activities of the majority of the components that make up a vehicle.

The case of Fujitsu exemplifies the case of the systems integrator of a hard disk drive network that successfully managed the introduction of a new product architecture, stemming from a major technological breakthrough embodied into the magneto-resistive head, a component that displaced the pre-existing mechanical-based technology (bottom left in figure 5). Chesbrough and Kusunoki (2001) argued that the success of Fujitsu during the shift from the old to the new technology was due to its systems knowledge. During the modular phase, Fujitsu, like other firms, relied on a decoupled network of external suppliers. Unlike the other firms that fell into what the authors called the "modularity trap," however, Fujitsu continued to invest "in systems knowledge and materials and component technology in its R&D labs" (Chesbrough and Kusunoki, 2001: 218). Fujitsu's systems knowledge went well beyond the range of products and components that the company produced in house. It enabled the firm to master the new, fast-moving technology and to navigate the dangerous waters of architectural innovation stemming from it. By knowing more than it needed for its own design and production, Fujitsu managed to avoid potential traps such as those described by Chesbrough and Kusunoki (2001) and Henderson and Clark (1990).

Chesbrough and Kusunoki's prescriptions about organizational arrangements remained confined to the two classical ones, however, namely, modular (i.e., decoupled) or integrated (i.e., tightly coupled). They did not emphasize the analytical importance of their findings that Fujitsu maintained technological capabilities well beyond those needed to perform the design and production activities tailored to modular architecture. Such technological capabilities enabled Fujitsu to manage uneven technological advances (i.e., magneto-resistive head vs. mechanical-based technology) and particularly to introduce new product architectures.

DISCUSSION AND CONCLUSIONS

We have argued that in complex products like aircraft engines, firms are capable of adjusting to the differing organizational requirements related to integral and modular innovations by maintaining a loosely coupled network structure. A key characteristic of loosely coupled network organizations is the presence of a systems integrator firm that outsources detailed design and manufacturing to specialized suppliers while maintaining in house concept design and systems integration capabilities to coordinate the work (R&D, design, and manufacturing) of suppliers.

We showed that in addition to capabilities to deal with unpredictable product-level interdependencies, assembler firms develop in-house capabilities in order to tighten (at least temporarily) their links with outside sources. This may happen for two reasons. First, advances in knowledge may lead to a potential order-of-magnitude increase in performance in one part of the system based on a fast-moving technology. Second, innovative opportunities may emerge from specialized suppliers in fast-moving technologies. In either case, assembler firms will need capabilities to deal with potential imbalances in component performance and to experiment with new system architectures. A cognitive overlap between assemblers and suppliers is therefore needed.

The concept of loosely coupled organizations is relevant also in other industrial contexts. For instance, the analysis by Orsenigo, Pammolli, and Riccaboni (2001) of pharmaceutical firms and their linkages with biotechnology firms hints at the existence of loosely coupled networks in drug development. Imbalances in the rate of improvement between electronics and mechanical technologies also led to loose coupling in the development of numerical control techniques (Mazzoleni, 1999). And there is more general and long-standing evidence of loose coupling between the large-scale manufacturing firms and suppliers of their production machinery and other inputs (Rosenberg, 1976; Patel and Pavitt, 1994). The empirical part of this paper needs to be extended by systematically applying the technology and product-level categories of our framework to other sectors that exhibit different degrees of product and technological complexity.

The framework captures some key aspects of the processes that have characterized the adjustments of the networks embedding the world's leading aircraft engine manufacturers and their suppliers. We have assumed that the technological and product dimensions play a key role in affecting the emergence of different organizational forms. As the case of Company B shows, other variables are at work that influence the make-or-buy decision process in multitechnology firms but are not captured in our analysis. These variables may be related to appropriability conditions as well as to firms' perception of specific technologies, in turn linked to past investments in R&D projects, the emergence of organizational coalitions with particular interests, and the like. It would be useful to extend this analysis by studying how different groups within firms develop a common perception of the strategic role of specific technologies and components and the innovative opportunities they open up.

The framework developed in this paper builds on a strong research tradition in organization theory that has identified technology as a key determinant of organizational structures (Perrow, 1967; Lawrence and Lorsch, 1967). Our framework extends this approach and opens up new avenues of research to understand better the relationships among technological change, product evolution, and organizational design. For example, more effort needs to be devoted to studying what firms know (as opposed to what they do) and how they know it, as learning processes increasingly rely on mechanisms other than doing (Pisano, 1997). Also, learning processes are embedded in dense networks that link systems integrators to suppliers of components and specialized knowledge. The increasing specialization of knowledge production poses serious challenges for large integrated firms.

The ideas this paper proposes provide a new perspective within which to interpret the increasing emphasis that both practitioners and scholars put on the role of networks, virtual forms, and other organizational arrangements that cut across firms' boundaries. The idiosyncrasies of knowledge as an input to productive activities are likely to make the market alone an inadequate coordination mechanism. Despite the fact that firms rely more and more on learning mechanisms other than "doing" (Pisano, 1997), the clear division of labor in knowledge production envisaged by Arora and Gambardella (1994) is likely to emerge only in rather specific circumstances, namely, when changes in the relevant bodies of knowledge do not cause imbalances, and product interdependencies are predictable.

This paper also suggests that there is no one-to-one mapping between product architecture and organizational architecture, as put forward by some of the advocates of modularity (Sanchez and Mahoney, 1996). Our framework provides a first answer to apparent paradoxes such as that stressed by Langlois (1997: 83), in which the adoption of a modular product architecture (i.e., the IBM S360) led IBM to integrate the production of previously outsourced components. If, as suggested by Langlois, this is related (among other things) to the shift from vacuum tubes to solid-state components, one can argue that the imbalance created by two component technologies (one mature, the other fast moving) led IBM to integrate vertically in order to coordinate the new component into its new, modular system. The adoption of a modular product architecture per se does not lead to a modular pattern of organization (i.e., decoupled network organizations).

The analysis of loosely coupled networks also provides the possibility of reconciling the traditional juxtaposition between component and architectural innovations and the organizational challenges they present. Henderson and Clark (1990: 28) pinpointed that "[a]n organization that is structured to learn quickly and effectively about new component technology may be ineffective in learning about changes in product architecture." By relying on loosely coupled networks, systems integrators can delegate component-level development activities to specialized firms. At the same time, by maintaining knowledge of the whole product system, they can coordinate the design and manufacturing activities within the network. Besides coordination, systemic knowledge allows systems integrators to spot promising new areas of development that may lead to architectural changes.

Loosely coupled networks are likely to become even more important in future. The continuing growth and specialization of knowledge production will make firms' external knowledge relations even more important. Advances in information and communication technologies will both facilitate the exploration of design alternatives in loosely coupled structures and open possibilities for more complex systems. Loose coupling is here to stay, and some firms will continue to know more than they need for what they make.

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