Unpacking the Black Box of Modularity: Technologies, Products and Organizations

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This paper explores the issues of knowledge and organizational coordination that stem from the adoption of modular product architectures. Modularity is a common characteristic of the products we have studied: aircraft engines and chemical plants. In contrast to much current research on product and organizational design, we argue that knowledge and organizational coordination cannot be achieved by relying only on automatic mechanisms enabled by the modular product architectures. Rather, the achievement of knowledge and organizational coordination demands interactive management of the actors and activities involved. This coordination role is played by companies that we define as 'systems integrators'. We contend that achieving knowledge coordination demands that systems integrators be able to span capabilities over a range of technological fields that is wider than the range of activities that they actually perform in-house.

Industrial and Corporate Change Volume 10 Number 1 2001

1. *Introduction*

The relationship between product and organizational design has attracted much attention in industrial practice and academic research. Practitioners are interested in understanding to what extent they can rely on external sources to design, produce and market their products. Academic researchers have tried to identify a set of general principles from which to assess alternative product configurations and to predict where the line between in-house and external activities can most effectively be drawn.

Recently much of the debate on product and organizational design has revolved around the concept of modularity. Originally, modularity was put forward as a product design strategy aimed at defining a standardized set of interfaces among components. Each component is allocated a specific function to be performed with respect to the given interfaces. These, in turn, are not allowed to change during a certain period of time (Ulrich, 1995). Subsequently, modularity has been used by scholars of strategic management and industrial economics to analyse organizational design, inter-firm relationships and knowledge dynamics (Arora *et al.*, 1998; Sanchez and Mahoney, 1996).

These heterogeneous contributions have highlighted the complex relationships between products, organizations and knowledge. However, no attempt has been made to give an integrated account of the different dynamics underpinning these relationships. This paper is a first step in this direction. We raise some analytical issues left unanswered by current research on product, organization and knowledge modularity. We argue that the concept of modularity carries different managerial implications at different levels of analysis. In order to develop a coherent framework within which to study these implications, we discuss the concept of systems integration.

The key research questions that we aim to address are: (i) are product modularity, organizational modularity and knowledge modularity positively correlated? (ii) If so, what are the implications for firms' disintegration strategies and the ensuing division of labour? (iii) To what extent is inter-firm coordination achieved through arm's-length market relationships? Is conscious coordination still necessary?

We empirically investigate these issues in two industries, namely aircraft engines and chemical engineering. The main arguments of this paper are the following. Product modularity, organizational modularity and knowledge modularity follow different dynamics. Both the aircraft engine and chemical engineering industries are characterized by increasing product modularization that entails greater division of labour across firms. Inter-firm coordination is not achieved through arm's-length relationships, however. It requires conscious coordination performed by all-round knowledgeable firms that we label systems integrators.

Therefore, increasing product modularization brings about two related effects: (i) greater specialization entailing greater division of labour across firms at the product level and (ii) conscious coordination performed by systems integrators at the organizational and knowledge levels. These two effects are not mutually exclusive, but they underline that there is no one-to-one mapping between product, organizational and knowledge modularity. In the light of this, despite the unquestionable and increasing relevance of strategic outsourcing, the data we present do not reveal a pattern of division of labour between architectures and module developers coordinated through arm's-length market relationships. Correspondingly, design outsourcing decisions and manufacturing outsourcing decisions follow different logics. In fact, design is outsourced to a lesser extent than manufacturing.

The paper is organized as follows. Section 2 discusses previous works on the concepts of product, organizational and knowledge modularity. Section 3 describes the research methods we employ to address the research questions. Section 4 presents a description of the sectors we analyse and the factors impinging upon systems integration. Sections 5 and 6 present the industry studies, and Section 7 offers conclusions.

2. *The Concept of Modularity: Implications for Products, Organizations and Knowledge*

This section introduces and defines the terms of our contention about product, organization and knowledge dynamics. We briefly review some contributions that focus on specific aspects of modularity. We underline some of the unanswered questions and discuss the concept of systems integration.

Building on previous studies on innovation dynamics and product architecture (Abernathy and Utterback, 1975; Abernathy and Clark, 1985; Clark, 1985), Henderson and Clark (1990) and Henderson (1992) moved the research focus from industry to firm issues. An architectural innovation is defined as a change in the relationships between a product's components which leaves untouched the core design concepts it embodies. Organizations are built around stable product architectures. The product architecture defines key functional relationships, information processing capabilities, communication channels and information filters. Once a dominant design has emerged, it is encoded and thus becomes embedded in the organizational set-up, which is why architectural innovation represents such a subtle and dangerous challenge for incumbents. While leaving the relevant technological capabilities unchanged, an architectural innovation alters key, yet tacit, interfaces (Henderson and Clark, 1990).

As Henderson (1992, p. 127) makes clear, the distinction between component and architectural knowledge would not make sense if 'information about the design of every element of the [product] could be costlessly and instantaneously transferred to all designers'. But since this transfer is expensive, architectural knowledge is needed to let each designer know what he or she needs to know, and nothing more, about other components' specifications (i.e. the interfaces). Thus 'architectural knowledge can emerge only after an organization has developed sufficient experience with a problem to be able to fragment it into elements without losing critical information' (Henderson, 1992, p. 127). Once an organization recognizes an architectural innovation as such, it has to change its 'orientation from one of refinement within a stable architecture to one of active search for new solutions' (Henderson and Clark, 1990, p. 17). But 'learning about changes in the architecture of the product is unlikely to occur naturally' (Henderson and Clark, 1990, p. 28). Not only does learning about the architecture require conscious effort, it also may entail different kinds of organizations, people and skills. This, we argue, is the link with the current research that analyses the division of innovative labour between companies specialized in the design and production of a few components and companies focused on architectural development.

2.1 Product and Organizational Modularity

Ulrich (1995) has provided the fundamental first step to reach a finer-grained understanding of the strategic issues underpinning the choice of a specific product architecture. Ulrich (1995, p. 419) defines product architecture as 'the scheme by which the function of a product is allocated to physical components'. The product architecture encompasses: (i) the arrangement of functional elements, that is, how the different functional requirements are structured in order to contribute to the total product performance; (ii) the mapping from functional elements to physical components, that is, which component implements which function; and (iii) the specification of the physical components' interfaces. According to Ulrich, the composite interaction of these dimensions determines the typology of product architecture. In a modular architecture, there is a one-to-one mapping between physical components and functional elements, and the interfaces between components are de-coupled. An integral architecture is instead characterized by a complex mapping between physical components and functional elements, and coupled interfaces between components.

The choice of product architecture is dictated by the company's product strategy. Ulrich contends that if a company wants to stress product performance, then the most appropriate choice would be the integral architecture, since global performance characteristics are optimized through this type of architecture. On the other hand, companies wanting to emphasize product change and variety, flexibility and upgradability may well choose a modular architecture.

It is worth noting that the definitions of modular and integral architectures proposed by Ulrich are to be understood as ideal types. Most products do not fully satisfy the requirements of either of them and therefore lie somewhere along a continuum that goes from fully modular to fully integral architectures. Modularity is a matter of degree. Correspondingly, the degree of modularity depends on the level of analysis. Products can be decomposed at different levels: subsystems (e.g. control system), sub-subsystems (e.g. fuel metering unit), components (e.g. valve) and subcomponents (e.g. spring). Accordingly, modularity can be a characteristic of each or only some of these levels.[1]

Sanchez and Mahoney (1996) stress the potential benefits of modular architecture, and recognize it as a powerful design paradigm, both for products and for organizations. Their main argument is that, due to advanced knowledge about component interactions, a set of interfaces can be fully specified and standardized. As a consequence, the design of architecture and modules can be de-coupled and carried out independently. This de-coupling has profound implications for a firm's product design and its underlying organizational processes. In fact, since changes to component interfaces are not permitted within a certain period of time, the 'processes for developing component designs become loosely coupled' (Sanchez and Mahoney, 1996, p. 65). As stated in Radner (1992), a modular architecture would create an 'information structure' that smoothly coordinates loosely coupled design teams. Similarly, the 'information structure' would also act as a 'compensation mechanism' that holds the loosely coupled systems together (Orton and Weick, 1990).

2.2 Knowledge Modularity

A step forward was made by Arora *et al.* (1998). They contend not only that can the production of new products be conceived in terms of the production and combination of modules, but also that the knowledge underlying such products is a matter of 'mixing and matching' modules. Since knowledge is considered as sharing some of the characteristics of public goods, knowledge modules are readily available to firms, which can concentrate either on the production of new modules or on the combination of them according to their geographical location. This argument is based on the assumptions that 'relevant information for innovation, whatever its source, can now be cast in frameworks and categories that are more universal' (Arora and Gambardella, 1994, p. 524).

According to Arora and Gambardella, advances in the theoretical understanding of problems, instrumentation and computational capability have given impetus to the use of general and abstract knowledge. Abstract

[1] In this respect the products analysed in this paper differ from traditional studies on product modularity that focus on simple products such as bicycles, trolleys and disk drives (e.g. Ulrich, 1995).

knowledge is understood as the ability to represent phenomena in terms of a limited number of essential elements, whereas general knowledge is described as knowledge that relates the outcome of a particular experiment to the outcome of other, more 'distant' experiments. This evolution of an industry knowledge base would pave the way to an increasing division of labour across companies. Different companies would focus on different components or activities within a given architecture. Other companies would specialize in the 'mixing and matching' of these components.

2.3 Technology, Products and Organizations: toward Modular Dynamics?

The foregoing discussion has highlighted the managerial implications of modularity in products, organizations and knowledge. To sum up, the evolution of an industry knowledge base into more general and abstract categories would allow for a better understanding of the 'inner workings' of products and processes. Such an understanding would enable the adoption of more complex design strategies (e.g. modularity). In turn, firms would de-couple the development of the architecture from the development of the modules, and then focus their activities on either the architecture or a few modules. Further, since the product architecture acts as a sort of 'glue', the organizational processes underlying architecture and module development can also be separated and carried out independently. The combined effect of the different dimensions of modularity would pave the way to a greater division of labour both within and across firms. Therefore, the literature on modularity contains a number of very strong predictions: (i) there exists a positive correlation between product, organizational and knowledge modularity; (ii) modular product architectures enable increasing specialization, both within and across companies; and (iii) modular product architectures allow for coordination to be achieved with minimum managerial effort.

In the following sections we acknowledge that modularity represents a very powerful concept with cogent managerial implications. Companies designing engineered products use modularity as a design strategy in order to exploit a number of advantages. A modular architecture enables companies to upgrade their products throughout their life cycle. This is particularly important in those industrial sectors where the product life cycle is much longer than the components' life cycle. Modularity also reduces production costs and time. In the case of chemical engineering activities, for instance, different modules can be built in parallel and off-site (thereby also increasing safety). A modular product is easier to maintain. As a result of these points, firms able to offer modular products use modularity as a marketing tool.

Based on our industry studies, however, we contend that the literature on modularity fails to recognize the different, though intertwined, dynamics underpinning products, technologies[2] and organizations. We argue that modularity is one of the driving forces that enable a greater division of labour across firms. This increased division of labour, however, demands tight cross-company interaction, and conscious efforts at coordination at both the knowledge and organizational levels.

Product modularity hints at the existence of one-to-one mapping between physical modules and organizational units embedding component knowledge (Henderson and Clark, 1990; Sanchez and Mahoney, 1996). Thus, the relevant physical interfaces would define the critical organizational interfaces, both within and across companies. The relevant organizational interfaces may be different according to the activity considered, however. In particular, conceptual design of heavily engineered products demands flexible, highly interactive organizational set-ups, wherein the relevant, and numerous, engineering disciplines are allowed to interact and be cross-fertilized, whereas later design stages and manufacturing activities may well be organized more rigidly along disciplines and physical component interfaces.

The absence of one-to-one mapping between product and organizational interfaces renders the achievement of coordination a task worth specific analysis. We examine the role of systems integrator companies and argue that these companies act as knowledge and organizational coordinators to guarantee the overall consistency of the product and to orchestrate the network of companies involved in the various stages of design and manufacturing. We can identify two dimensions of systems integration—static and dynamic. Static systems integration is aimed at achieving technological and organizational synchronization within established product architectures. Dynamic systems integration is understood as the ability to search and explore alternative paths of product and process configurations (Steinmueller, personal communication). This ability requires a wide technological base (Prencipe, 2000), a well-grounded understanding of the evolution of customer needs and a good deal of luck! We argue that in order to develop and maintain this capability systems integrators have to be knowledgeable in different technological fields (e.g. fluid-dynamics, electronics and chiral chemistry) as well as different activities (e.g. conceptual design, detailed design and manufacturing).[3]

[2] In this paper we understand technologies as bodies of knowledge. See Pavitt (1998) for a discussion.

[3] Our understanding of systems integration capability is broader than the notion of absorptive capacity

Furthermore, the concept of modularity itself, as put forward in the current literature, is *ex definitione* static. Following Sanchez and Mahoney (1996), the product architecture allows components to change within a predefined range of variation. This range is not permitted to change within a set period of time that can span from the product development process through the entire product life cycle. This affects both the development processes of components and their underlying organizational processes to the extent that the latter can be divided among different organizations. This static feature of modular product architecture means that in the long term a modular architecture can fail to accommodate changes in single modules. A modular architecture can have detrimental effects, particularly when the underlying technology of one specific module is changing much faster than the others are (Pavitt, personal communication).

This section has discussed the limitations of the current literature on modularity and the terms of our contention. The discussion of the factors that impinge upon systems integration activities in the two industries studied will be carried on in Section 4. The next section describes the research method employed in the study.

3. *Research Method*

This paper is based upon two detailed industry case studies. Our research was conducted in two industrial settings that share several features, as reported in Section 4 below. We coordinated our research designs and, following Iansiti and Clark (1994), merged the results of the two studies. Each study is based upon a multiple case research strategy. As we adopted an embedded design we carried out firm level analysis in order to reach conclusions related to the dynamics of the division of labour at the industry level.

Three distinct types of data were employed in this study to establish construct validity (Yin, 1994). Multiple data sources enabled us to obtain stronger substantiation of constructs by triangulating evidence across cases. The first type of information was gathered from a systematic review of the technical literature, trade publications, specialized engineering journals, company annual reports and publications. These data were used to provide background information and to sketch an overall picture of the sectors analysed.

The second type of information used in the research is quantitative evidence

as put forward by Cohen and Levinthal (1990). Not only do all-round knowledgeable systems integrators monitor external sources of technologies, but they also actively pursue technological and organizational coordination. In this way, systems integration capability assumes a proactive attitude.

from two sector-specific databases. With regard to the aircraft engine industry, we make reference to an original data set designed by rearranging the US Patent Office classes.[4] The database encompasses patent data related to the major engine makers and suppliers of the aircraft engine industry between 1977 and 1996. Patents are rearranged according to a detailed sector-specific taxonomy that relates each patent to a specific engine component or subsystem. The taxonomy was validated by collaborating with two primary examiners of the US Patent Office, as well as with practitioners. This information was used to assess the technology strategies of engine makers over time.

With regard to the chemical engineering study, Independent Project Analysis, Inc. (IPA, from now on) provided access to a unique proprietary data set encompassing project-level data about more than 3000 chemical projects (larger than US$5 million) executed worldwide between 1985 and 1997. These data refer to projects throughout the chemical industry (excluding pharmaceutical and biotechnology-based processes). IPA gathers information using in-depth structured interviews aimed at collecting evidence on both the technological aspects and the organizational practices that impinge upon each project stage. Further, the data discussed here are normalized by project size and degree of technological novelty. The results thus refer to the 'average' project carried out in the industry. These data were used to evaluate the effects of changing patterns of division of labour across firms at the project level.

The third type of information came from interviews. For the aircraft engine industry we interviewed industry experts and company engineers from fourteen companies (the major engine makers and suppliers in Western Europe and the USA). In total, we conducted forty-five interviews, which included both phone and face-to-face interviews. For the chemical industry, we carried out a set of forty interviews. They involved four industry experts and chemical engineers from fourteen companies. Background evidence was gathered through interviews with chemical engineers working for design software vendors and specialized consultants. The length of the interviews was 1–3 hours. Interviewees were senior people, such as the Vice President of Technology, Technical Directors of the Advanced Engineering Department, the Chief Process Engineer and the Head of Design Technology. All were either currently or formerly involved in design activities.

Data from these interviews were elaborated to produce case histories of the companies involved in the study. Qualitative insights provided by interviewees proved to be fundamental for understanding the knowledge

[4] For a full account of the method of compilation of the database see Prencipe (2000).

requirements underlying the patterns of division of labour described by the quantitative data. This stage has enabled us to identify, evaluate and match patterns as they emerged from 'within-case' (Eisenhardt, 1989, p. 540). We then cross-compared the cases within and between each industry. As we followed a multiple case research design, we adopted a strategy of replication in multiple empirical settings in order to establish external validity (Yin, 1994).

4. *The Driving Forces Impinging on Systems Integration*

In this section we discuss the driving forces impinging upon systems integration in the aircraft engines and chemical engineering sectors.[5] The combined effect of these factors 'enables and pushes' systems integrators towards greater externalization of activities and correspondingly leaner organizational structures.

The first set of driving forces described below has been labelled 'enablers'. Enablers directly affect the nature of the systems integration activities. On the other hand, we have labelled the other set of driving forces 'pushers' as they literally push systems integrators to hive off larger chunks of the activities related to design, development, and manufacturing (Table 1).

4.1 The Enablers

Internal accumulated technological knowledge related to the overall product enables systems integrators to better understand the behaviour of components within their operating environment. This ability rests upon advances in scientific and technological disciplines, complex mathematical models, design knowledge embodied in people, and operational experience. The use of powerful computers and sophisticated computer models has underpinned the progress of knowledge in these industries. For instance, in the example of the aircraft engine, computational fluid dynamics codes have allowed engine designers to optimize the shape of turbine and compressor blades. These codes, however, are always validated using empirical data related to engine behaviour and performance stored in databases held by engine makers. The same holds true for large chemical operators. The reliability of software for process simulation crucially depends upon the quality of the data used as

[5] The two sectors we have studied share the characteristics of a group of industries that have been labelled complex products systems. For a comprehensive discussion see Miller *et al.* (1995) and Hobday (1998).

TABLE 1. Driving Forces Affecting Systems Integration

Enablers	Pushers
• Internal accumulated technological knowledge of product behaviour	• Spiralling costs of development, construction and retrofitting
• Accumulated technological knowledge of components suppliers	• Pressure from developing countries
• Knowledge codification process	• Cut of defence budget entailing personnel reduction (aircraft engine)
• Increasing use of ever more powerful computational capacity	• Advantages of specialization at supplier level
• Increasing modularization of the system and of the construction activity	• Shrinking profit margins
• Technological maturity (chemicals)	

inputs. This set of data is eminently plant-specific. In both industries, databases represent an important and extremely valuable part of the organizational memory of systems integrators. In the same way, the experience of engineers and rules-of-thumb are still prominent in the choice of new design routes.

In the case of the aircraft engine industry, a better understanding of the technological principles governing the engine system has enabled manufacturers to conceive aircraft engines in terms of basic modules. In particular, engine makers can specify component interfaces in terms of their functional and spatial specifications as well as their physical properties. Thus, most complex interactions take place within the same modules rather than across them. Modular aircraft engines have been in existence since the early 1970s. From an operational viewpoint, the concept of a modular aircraft engine has its origins in the efforts of engine makers to standardize component parts to facilitate the maintenance of engines in use. The modular design philosophy is common in the industry. Through its adoption, manufacturers can launch engine families rather than single engines and take advantage of the associated cost benefits. Using common cores, engine makers can spread the recovery of non-recurring design costs over several market segments and benefit from larger-scale production. Thrust ranges can in fact be targeted by the addition of a low-pressure system tailored to the engine. Modularity in this industry has also paved the way to the practice of 'retrofitting' and 'design commonality' whereby manufacturers improve existing engine variants by introducing technological modifications, which, in turn, permit performance improvements within the same thrust range.

Modular chemical plants have been widely commercialized since the early

1970s with the diffusion of off-shore oil extraction facilities. Furthermore, technological maturity has enabled chemical firms to rely to an increasing extent on licensed processes as well as the engineering capabilities of contractors. Cost reduction is one of the main drivers of equipment modularity. Off-site module construction reduces risks and time. For instance, support buildings and modules can be built in parallel and fitted into one another afterwards. This saves time and makes component construction safer, it being carried out at dedicated, off-site, facilities. In addition, modularity simplifies the project manager's duties. First, it allows for better scheduling of activities (de-coupling the construction of different pieces of equipment and support buildings). Secondly, it allows for better control of activities. For instance, it is easier to identify who is responsible for a delay. Finally, modularity simplifies retrofitting and revamping operations, reducing shut-down time and thus costs.

4.2 The Pushers

Both industries are characterized by a dense network of collaborative agreements covering the design, development and manufacture of new products. Since the 1980s, systems integrators have tried to involve a larger number of chemical contractors and aircraft engine suppliers in the development of new products or processes. In the case of the aircraft engine, this practice has been borrowed from the military side of the industry. The reasons for the development of a new engine being split amongst different companies lie in the increasing development cost and related risk of failure of the programme. Competition in the large turbofan market is cut-throat and price-based. Industry trade journals report that engine makers set preferential prices in order to secure a foothold in the spares market business, which is considered to be the 'gold mine' of the industry.

Engine projects are developed using a new form of contractual relationship, labelled risk and revenue sharing partnership. Accordingly, suppliers (also labelled risk and revenues sharing partners, or RRSPs) are invited to join the engine project early on and buy a stake in it (usually related to one or more components or an entire subsystem) in order to share the risks and future revenues (if any) of the project. The shares held by suppliers have been increasing over time. On the one hand, systems integrators want to 'split' risks and revenues across several suppliers to reduce their own stakes and to gain customers (i.e. airlines) via the involvement of suppliers of the same nationality of the customers. According to some industry experts, airlines (usually state-funded) are more likely to place an order for engines when national component suppliers have been involved in the project. On the other hand, component suppliers, especially from developing countries, push to get a bigger share of an engine project in order to learn about more engine parts.

Contractual agreements similar to RRSP have also been adopted in the chemical industry. Under such agreements operators involve contractors in the conceptual design stage. Thus, contractors share the risks connected with the feasibility studies and technology validation. They bear part of the development costs by supplying their own engineering capabilities, and they reap the reward of being awarded the contract (without bidding procedures) to build the plant if the design package is sanctioned. Further, they establish stable relations with the operators they cooperate with and develop up-front the design capabilities that most contractors traditionally lack. Operators use these agreements to access the detailed engineering capabilities they have largely got rid of, and thus save on engineering costs. In addition, contractors have a better understanding of the procurement and construction process which helps reduce expensive and time-consuming on-site reworking, through a better definition of the design package.

5. *The Aircraft Engine Industry*

The aircraft engine sector is an oligopolistic industry. The large turbofan market is dominated by the so-called Big Three, notably General Electric Aircraft Engines, Pratt & Whitney and Rolls-Royce. In the medium- and small-sized engines market, the main actors are AlliedSignal Engines, Allison Engines (now a division of Rolls-Royce), Pratt & Whitney Canada, Williams International and two international joint-ventures, CFM International and International Aircraft Engines.[6] Then there are the RRSPs, such as MTU, Snecma and Fiat Avio. First and second tier suppliers complete the scene.

5.1 Product Characteristics and Knowledge Requirements in the Aircraft Engine Industry

The aircraft engine industry is characterized by a product with a high number of components and subsystems. These components may differ in kind and variety. They can belong to different and often distant technological fields. The high number of components can increase even further over time, as firms have to cope with the evolving needs of customers as well as ever-tightening

[6] CFM International was set up by General Electric and Snecma; International Aircraft Engine (IAE) comprises Pratt & Whitney, Rolls-Royce, Motoren und Turbinen Union, Fiat Avio and Japanese Aircraft Engine (a consortium of Japanese aircraftspace companies).

regulations. The aircraft engine also shows strong interactions across components and subsystems at the product level.[7] The wide variety of technological disciplines involved in engine design and development requires engine makers to maintain skills that span several technological fields (Prencipe, 1997).

Systems integrators also need to have a clear understanding of customers' requirements. In the civil aircraft engine industry, the customer is the airline placing the order. However, it is the aircraft manufacturer that provides the specifications. Also, engine makers have to comply with the rules and regulations established by the certification authorities, such as the FAA in the USA and the EJAA in Europe. There is a close, dialectic and ongoing dialogue between engine makers and certification authorities during the design and the development of new engines. Safety requirements add an important constraint to the application of new technologies. The dialogue ends with the certification of the engine after the prolonged and arduous test procedures have been carried out by the manufacturer.

The fact that the introduction of new engine parts based on innovative technologies is discussed between engine manufacturers and the certification authority does not in any way reduce the importance of feedback as mediated by the market. Information related to engine behaviour gathered by airlines and maintenance engineers is deemed by engine makers to be of extreme value during the innovation process. One of our interviewees underlined that the acquisition of maintenance companies by engine makers in the last five years has added as a by-product an important source of information about customer requirements.[8] The acquisition of information related to engine behaviour is now facilitated by digital engine control technologies that have replaced hydromechanical ones. Digital engine control units, also labelled FADEC (i.e. full authority digital engine control), are in fact able to monitor and store engine performance data throughout an engine's life.

Thus, engine makers' activities span different knowledge domains: the scientific and technological fields underpinning the wide variety of engine subsystems; the organizational (e.g. project management) capabilities

[7] It is worth noting that the strong interactions that characterize the aircraft engine at the product level are not incompatible with the notion of a modular aircraft engine. In fact, modular design allows for 'loose coupling' components interactions at the design level, which is different from 'tight or loose' in an actual product. As Sanchez and Mahoney (1996) have pointed out, the design of a personal computer may involve loosely coupled component interactions in that different components (e.g. the microprocessor) may be substituted within a certain range dictated by the architecture into the computer design without requiring a redesign of the other components. The components in the physical computer, however, must be tightly coupled in the sense that all components must function in unison in order for the computer to function as a system.

[8] It is worth noting, however, that the main reason why engine makers have entered the maintenance business via acquisition is because of the increasing profit margins characterizing this business, as opposed to the nearly negative cash flow deriving from the sale of aircraft engines.

required to manage and integrate the actors involved in the industry; knowledge about client requirements; and knowledge about the regulations for engine certification. The 'core capabilities' of the engine maker lie in its ability to identify business opportunities, and translate regulatory and customer requirements into product specifications that can be met by its technological capabilities.

5.2 The Role of the Systems Integrator

Accumulated knowledge about component behaviour as well as about the entire system has enabled systems integrators to decompose the engine more effectively and focus on a few 'soft' capabilities, such as software codes, rather than 'hard' ones, such as manufacturing. Our interviewees, in fact, confirmed that manufacturing is no longer deemed critical for the integration of the engine, whereas design and development play much more prominent roles. Within the design activities engine manufacturers focus more on conceptual design, leaving detailed design to suppliers or RRSPs.

As mentioned earlier, the design, development and manufacturing activities of the aircraft engine are split amongst a large number of component suppliers. An industry expert argued that 'if I want to make a list of these 10,000 [engine] parts and I want to put a price against each of them, then the actual name of the supplier, I think you will find between 60–80% of the total value is outside the systems integrator'.

A cursory look at Table 2 confirms this. The table reports the shares of in-house design and manufacturing of engine makers and RRSP companies. In the case of engine makers the shares refer to the entire engine in relation to design and manufacturing tasks performed. In the case of RRSP companies, the shares refer to the specific bit of the engine they are specialized in. The shares of in-house design and manufacturing have been decreasing over time, reflecting an overall trend towards greater externalization both at the design and at the manufacturing level. As regards systems integrators, the share of the design responsibility ranges from 100 to 70% in 1986 and from 80 to 50% in 1996. Manufacturing is less 'internal' since its shares were, on average, about 50% ten years ago, whereas they now range from 40% to less than 10%. According to Table 2, the systems integrators included in our sample have reduced their manufacturing responsibility by as much as half or by at least one-third. Company B is an exception as its responsibility has decreased nearly tenfold, from 50% to between 5 and 10% during the observed time period.

This trend towards greater externalization holds true also for RRSPs. Their

TABLE 2. Shares of in-house design and manufacturing of aircraft engine companies

	Design (%)		Manufacturing (%)	
	1986	1996	1986	1996
Systems integrator				
Company A	100	75	60	30
Company B	70	50	50	5–10
Company C	85	80	50	25
Company D	95	80	60	40
Company E	90	70	50	30
RRSPs and first-tier suppliers				
Company F	50	20	80	30
Company G	90	75	90	75
Company H	100	75	100	65
Company I	100	99	100	95

Source: authors' elaboration on interview data.

design responsibility varied between 100 and 50% in the mid-1980s, and between 75 and 20% in the mid-1990s. Likewise, the shares related to manufacturing dropped from 90% on average in 1986 to 70% in 1996. In the case of Company F, manufacturing nose-dived from 80 to 30%.

The decreasing shares of design and more especially manufacturing responsibility affecting both systems integrators and RRSPs reflects the increased ability of suppliers (first and second tier) to take on design and manufacturing. Systems integrators and RRSPs can take advantage of these more capable suppliers and subcontract to them larger parts of the engine, thereby also passing on to them the burden of some of the fixed costs. Thus, there is an increased specialization of the supplier base, leading to greater division of labour across the three different levels of actors involved in the industry. As highlighted in Table 2, however, there is a gap between design and manufacturing shares, reflecting the fact that systems integrators and RRSPs subcontract manufacturing to a larger extent than design. In other words, they outsource the production of some engine components and subsystems whose specifications have been drawn up in-house. This practice is also known in the industry as 'make-to-print'. Company F in Table 2 is an example of a 'make-to-print' company. Its manufacturing shares are always higher than its design shares, suggesting that it manufactures according to the drawings of systems integrators. This point was confirmed by interviewees.

Table 2, however, does not tell the whole story. As regards systems integrators, it is worth stressing the following points. The shares in Table 2 refer to the entire engine system, since our interviewees clearly stated that the core engine design is jealously kept in-house. The core engine design is the most critical for engine performance and therefore is a key product differentiator. Similarly, the shares related to design responsibility refer to overall design activities, as they do not distinguish between conceptual and detailed design. Engine conceptual design is always kept in-house by systems integrators. As argued by our interviewees, 'It is in the advanced design project [concept design] that you get the most clever stuff, such as how can you scale down this new version without impairing engine performance'. Also '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'.

Furthermore, the figures cut across all project-level (i.e. product) decisions. They represent an average of all projects carried out by systems integrators. Put another way, these shares do change across engine projects and within the same project over time. In fact, at the engine project level, systems integrators may decide not to take on design responsibility. As an overall company policy, however, design capability is always kept in-house via advanced research projects, engine demonstrator projects and continuous internal training. There is, therefore, a distinction between project-level (product) decisions and knowledge-level decisions.

The results discussed above lead to two interrelated points. The industry is characterized by a greater division of labour across firms than before. The driving forces discussed in Section 4 'enable and push' systems integrators to pursue deliberate product disintegration strategies. On the other hand, systems integrators pursue integrated strategies at the knowledge level. Integration at the knowledge level is indeed mandatory for systems integrators to 'compose' what they have 'decomposed'. This is epitomized in this passage, 'Without our integration capability spanning several technological fields we won't be able to decompose and then recompose the engine system'.

Furthermore, the effectiveness of the 'design split' within the same company and even more so across different companies seems, in fact, to depend on the capability of the systems integrator to understand how to decompose the system first and then, on the basis of such decomposition, to integrate it, inasmuch as, as one interviewee commented, 'those joint-ventures set up to design, develop and manufacture aircraft engines that do not have right from the beginning a proper and capable systems integrator usually end up in long and complex redesign processes, since when the time comes to put everything together the system may not work at all'.

The results discussed above square with the findings of Prencipe (2000).

Based on US patent data, we illustrated that the world's largest engine makers have capabilities that span a wide range of technological fields. These companies also maintain technological capabilities related to several of the outsourced components, and certainly well beyond what we have labelled the 'inner core' of the engine.

6. *Process Technology Developments in the Chemical Industry*

Following Freeman (1968), Landau and Rosenberg (1992) and Freeman and Soete (1997), the analysis focuses on the integrative activities of chemical engineers, and the interaction between large chemical manufacturers (operators) and specialized engineering firms (contractors). Chemical engineering, that is, the body of knowledge underpinning the activities of process design and development, is based largely upon the idea of creating a set of principles and techniques that make it possible to deliver any process by mixing and matching elementary 'unit operations' embodied in specific pieces of equipment. In short, chemical engineering activities seem to embody (by design, one might say) the features of a completely modular architecture encompassing both the products they deliver and the knowledge base they rely on.

However, we argue that alongside a trend favouring product modularity, technological and organizational integration capabilities are still needed in order to achieve inter-firm coordination. The persistent need for explicit efforts of coordination, as opposed to the impersonal coordination of the market, is examined by comparing the evolution of the traditional pattern of division of labour between operators and contractors.

6.1 Division of Labour in the Chemical Processes Industry

The traditional pattern of division of labour across the different stages of design and construction (conceptual design, detailed engineering, construction and start up) sees operators involved throughout the design process, either as leaders or as supervisors of other companies' activities. Contractors step in when conceptual design is defined and help to set out the detailed process engineering. Equipment suppliers and other support companies are pulled in once the detailed engineering has been completed and a plant layout is ready. Operators and contractors supervise construction. Once the contractor has proved plant operability, it steps back and leaves the management of the plant to the operators.

Within this three-tier structure neither operators nor contractors retain any manufacturing capability. Third tier equipment suppliers build components according to the specifications provided. Other suppliers are in charge of support buildings, control systems, construction and the like. In this respect, the differences between design and manufacturing decisions are even sharper than in the case of aircraft engines, where engine makers still maintain in-house manufacturing capabilities.

Like engine makers, chemical operators identify the process of translating business opportunities into technology requirements as their key 'core capability'. Achieving this translation (or 'mapping', as many interviewees termed it) is the chief aim of conceptual design. This is the design stage when overall project goals, scope and execution strategies are defined. Even though up-front design activities account for about 10% of the total installed cost, decisions taken at this stage influence from 70 to 80% of the final capital expenditure (Douglas, 1988). If changes to these early strategic choices occur, the execution phase ends up being very disrupted and costs can easily get out of control.

The major difficulty involved in conceptual design is related to the huge number of feasible process alternatives.[9] Thus, what the design unit of an operator has to do first is, in the words of one of our interviewees, 'to select out all those alternatives that do not deserve to be pursued any further' in order to produce a process flowsheet that describes the sequence of unit operations that deliver the product along with their connecting interfaces. Given its inherent complexity, this process synthesis phase requires a thorough understanding of the business opportunities, the chemistry of processes as well as the technological problems involved in the process scale-up.[10]

Once the conceptual stage is completed, and the project has been approved by top management, the execution phase starts. The project team establishes a timetable and a capital cost plan. From this stage onward, opportunities for radical changes are minimal. The main objective is to deliver a plant of given technical characteristics within the defined timetable and budget. Tasks, both between and within companies, are increasingly well defined according to the boundaries of engineering disciplines and the specific components to be developed.

Within this structure, contractors play a fundamental role in introducing and diffusing process innovations. Indeed, some contractors have maintained a position of long-term technological leadership in specific areas. In particular,

[9] The number of alternative routes amenable to delivering the same task is between 10^4 and 10^9 (Douglas, 1988).

[10] The scale-up process of a chemical route involves problems of its own, as it is not linear. This means that the basic chemistry of the process can change in moving from the laboratory bench up to the full-scale plant.

contractors have provided basic contributions in developing catalytic processes and delivering a stream of continuous engineering design improvements (Arora *et al.*, 1999). For instance, as Arora *et al.* (1999) point out, M. W. Kellogg retains capabilities related to ethylene processes and high-pressure ammonia synthesis, Scientific Design has developed routes to produce inputs to various synthetic fibres and plastics, and UOP provides proprietary refining technology.

However, in the main, contractors tend to maintain development capabilities within rather narrow ranges of processes (or even specific process steps). Furthermore, they are unlikely to develop new chemical products. They tend to step in once a large operator has established a new product market. Indeed, according to the traditional pattern of division of labour, operators take the lead in introducing radically new products and processes, as they can call on a wealth of empirical data and expertise accumulated in the course of running plants.[11] Therefore, operators are used to maintain wider sets of technological capabilities than contractors. Also, in the case of new chemicals or new underlying processes, operators traditionally do not rely on contractors' capabilities. Contractors are only involved with 'second generation' plants.

In the last decade, most operators in the petrochemical, hydrocarbon and bulk chemical business have implemented cost reduction programmes associated with the adoption of leaner organizational structures.[12] This has entailed a downsizing of their centralized process engineering departments and the reorganization of the residual design capabilities into matrix-like set-ups. The strategic idea underpinning this is a refocusing of the operator's engineering capabilities around what has come to be considered its real 'core capability', i.e. the capability of mapping market opportunities into technology requirements. As this 'mapping' is the aim of conceptual design activities, operators opted to outsource most of their detailed engineering.

The next section discusses the implications of this choice in terms of how design activities are organized.

6.2 Changing Division of Labour and Project Performance

The push towards flat organizations has changed the traditional division of engineering labour. Figure 1 shows that engineering contractors have been increasingly involved in high-level design activities. The data presented in Figure 1 have been normalized by IPA Inc. to accommodate differences in the

[11] UOP is an exception in this respect, as it runs its own refineries.

[12] The factors underpinning this process have been described in Section 4 (Table 1).

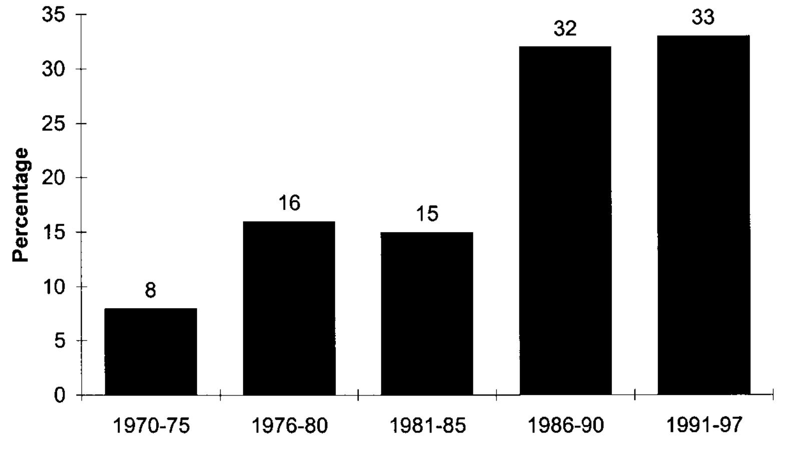

FIGURE 1. Percentage of projects with contractor-led definition. Source: adapted from IPA, Inc. database. These indicators are computed on a sample of more than 3000 projects executed worldwide, between 1985 and 1997. Data are normalized by project size and degree of technological novelty.

degree of technological novelty pursued by each specific project, and project size. Thus, the results shown refer to an 'average' project.

Despite the increasing involvement of contractors in high-level design decisions, all the operators involved in this study have retained in-house capabilities related to critical components. In particular, they maintain both conceptual and detailed design capabilities related to the reactor, which is the key component of the plant. Changes in this specific piece of equipment are likely to bring about systemic changes. Operators also maintain research units focused on the theory and modelling of reactor behaviour. Given the complexity and criticality of this component, fairly detailed calculations are necessary even at the conceptual stage, and their consistency with the overall flowsheet has to be checked continuously. In this respect, the technology-level decisions of chemical operators and aircraft engine makers are quite similar, as engine makers' outsourcing decisions are influenced by the criticality of the particular component involved.

A closer look at the dynamics of this disintegration process shows that, rather than contractors pushing to gain control of early stages of the design chain, operators are pulling in contractors to become involved in the earlier, conceptual stage. Interviews with both contractors and operators confirm the reluctance of contractors to take on risks related to conceptual design. Contractors' traditional strengths are in detailed engineering and effective project management. Once they become involved in the conceptual stage, they enter

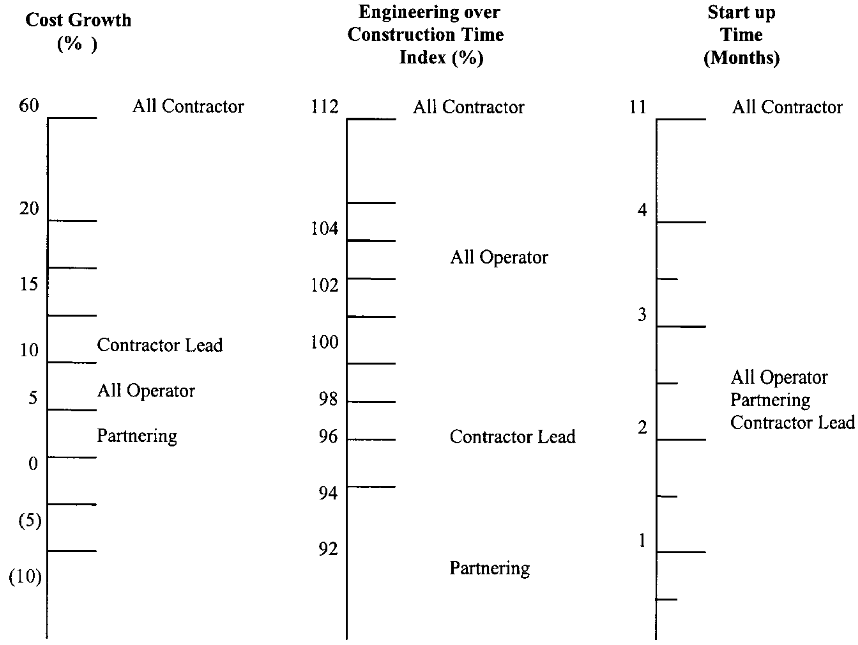

FIGURE 2. Division of labour and project performance. Source: adapted from IPA, Inc. database. These indicators are computed on a sample of more than 3000 projects executed worldwide, between 1985 and 1997. Data are normalized by project size and degree of technological novelty.

a different and much riskier business. Skills and expertise are demanded that in the main they do not possess. In particular, they generally cannot rely on plant feedback to improve their understanding of plant operability.

Although Figure 1 depicts an increase in the role of contractors, data provided by practitioners and from our interviews show that projects where contractors have full responsibility from the very early stages of project definition (with almost no input from the owner) exhibit the worst overall performance. Figure 2 presents performance indicators derived from cost growth (over the expected values), relative engineering and construction time (as a measure of the reworking necessary to bring the plant to operability), and start-up time (how many calendar months it takes to bring the plant to full scale operability).

However, not even the 'all operators' projects show outstanding results. As pointed out by many interviews, operators are finding it increasingly difficult to define the overall goals and technology requirements of their projects, due to the loss of experienced personnel. The best performers are the 'partnering' projects, where contractors are brought on board early and the lead is taken by the partner with the capabilities relevant to the project.[13]

Rather than a tight division of labour, good project performance more and more requires partnerships between operators and contractors. What was disintegrated on one side (in terms of in-house detailed design capabilities) has to be reintegrated by open and cooperative management of projects. Operators have tried to compensate for decreasing in-house capabilities (of a specific kind) by 'pulling up' contractors into different types of design activities.[14]

However, our case studies reveal that, despite the early involvement of contractors, operators tend to maintain a clear position of leadership and the contractor's engineers only become involved once the overall structure of the process flowsheet has been defined. This is particularly true of projects with a high degree of novelty. Contractors' engineers are expected to contribute by fine-tuning the process steps to the available equipment, or even to adopt innovative equipment specifications. Joint engineering teams are set up and information is shared as much as possible.

To sum up, a 'modular' pattern of division of labour between operators and contractors has not emerged. Although the range of activities that operators perform in-house has certainly decreased, the best performing projects are quite demanding in terms of the degree of cooperation and involvement of operators. The design package cannot just be delivered to the contractor to be executed. Even though the traditional allocation of tasks and responsibilities has changed, execution of a plant project requires a good deal of conscious effort devoted to coordination.

7. *Conclusions*

This paper has discussed the links between the dynamics of products, knowledge and organizational modularization in the aircraft engine and the chemical engineering sectors. We have argued that product modular-

[13] IPA's methodology labels as 'integrated' those projects characterized by a highly cooperative style of management. We preferred to rename this management style as 'partnering' to avoid confusion with the more specific meaning that economists attach to the word 'integration'. We are particularly grateful to an anonymous referee for signalling this problem.

[14] The question that cannot be answered in this paper is whether this increase in 'partnering' is the outcome of a conscious strategy, rather than the unintended consequence of the reaction to short-term cost pressures. As might be expected, the interviewees working for operators stressed the 'conscious strategy' explanation, while engineers working for contractors pointed out the 'ominous mistake' issue.

ization does not derive from, nor bring about, knowledge modularization. Further, the adoption of modular product architectures has complex implications in terms of the ensuing patterns of division and coordination of labour.

We contend that the diffusion of modularity as a design strategy is accompanied by an increasing division of labour across firms at the product level. Such an increase in specialization, however, as revealed by firms' outsourcing decisions at the manufacturing and design levels, demands tight cross-company interaction and conscious efforts on coordination at the knowledge and organizational levels. This observation sets our analysis apart from the dominant accounts of the impact of modularity on organization and knowledge (Sanchez and Mahoney, 1996; Arora *et al.*, 1998). Modular product architectures do not define clear 'information structures' capable of coordinating actors via smooth, arm's-length market relationships. In the cases we studied, product modularization called for highly interactive organizational set-ups. As a consequence, the dynamics of division of labour among companies is not as smooth as a completely modular world would actually permit.

The tension between specialization of activities on the one side and the need to actively manage technological and organizational interfaces on the other has been reconciled by discussing the role played by 'systems integrators'. Such tension reveals the fundamental point raised by this paper: the knowledge boundaries of the firm fundamentally differ from the boundaries of the firm as defined by make-or-buy decisions. In a nutshell, systems integrators 'know more than they do'.

This point is ignored by most of the research on product and organizational design, as it is commonly (and tacitly) assumed that the product components' interfaces always and necessarily define the relevant organizational interfaces. By extension, they would also define the relevant knowledge interfaces, as each component would embody all the knowledge modules relevant to the design and manufacture of the module itself. If you 'buy' a module, then you also 'buy' the knowledge it embeds. We have argued that our industry studies do not support this view, as knowledge and product dynamics follow different paths.

In fact, in the aircraft engine industry, systems integrators are not mere assemblers of physical components. Our findings have pointed to the fact that systems integrators still play a prominent role in the design, development and integration of the engine. Although they may not take on design and manufacturing responsibility for all components in one engine project, as an overall company policy they retain, in-house, a fundamental and integrated understanding of what they outsource. However, the nature and the content of systems integration capabilities have been greatly affected by several factors, such as knowledge codification processes, product modularity and increasing development costs. Systems integrators focus on the softer capabilities, leaving hard ones, such as manufacturing, to suppliers.

In the chemical industry we observed a rather different pattern of division of labour, although one consistent with our argument. The traditional division is between conceptual design, performed by large operators, and detailed engineering, performed by contractors. Recent competitive trends have induced operators to narrow the range of their design capabilities to reduce costs and lead time, and involve contractors in the conceptual stage to fill the gap. However, conceptual design is different from detailed engineering and is also much riskier. Most contractors have proved to be reluctant to become involved at such an early stage. As a consequence, wherever cooperative project set-ups have not been put in place, performance has worsened.

To sum up, our industry case studies put recent theorizing on the far-reaching effects of modularity in a critical light. We have pointed out that the role played by knowledge integrators is prominent in those sectors characterized by large and complex products. In fact, engineering knowledge is far from being modular and knowledge integration is not a matter of 'picking, mixing and matching' readily available knowledge modules. This paper is a first effort to unpack the 'black box' of modularity. Further research is needed to understand the micro-foundations of the modularization processes at the product, organizational and knowledge levels. Such research should aim at identifying the relevant dimensions of the modularity process at a more finely graded level of analysis to identify the different mechanisms at work.

Acknowledgements

This paper has benefited greatly from discussions with Eugenia Cacciatori, Aldo Geuna, Mike Hobday, Franco Malerba, Massimo Paoli, Keith Pavitt, Ammon Salter, Ed Steinmueller, Nick von Tunzelmann and two anonymous reviewers. An early draft of it was presented at a workshop held in SPRU, University of Sussex, 23–24 June 1998, and at the ETIC Conference, Strasbourg, 16–17 October 1998. Participants offered invaluable suggestions. The authors gratefully acknowledge financial support from the European Commission, TMR, Marie Curie Fellowship, from Bocconi University and from the British Engineering, Physical and Science Research Council (EPSRC). The usual disclaimers apply.

The authors' names are presented in alphabetical order. Sections 1, 2, 3 and 7 have been jointly written. Section 4 and 5 can be attributed to Andrea Prencipe, and Section 6 to Stefano Brusoni.

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