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Problem solving and the Co-ordination of Innovative Activities

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1. INTRODUCTION

Over the past ten years many authors and pundits have publicly discussed the changing role of the large, integrated, innovating firm. In the context of increasingly globalized markets, ever more complex supply chains and international manufacturing networks, corporate decision-making processes involve more and more actors, variables and criteria. This is a challenge for corporate head quarters. Many have argued that the role once attributed to the integrated innovating organisation and its R&D laboratories is increasingly associated with the functioning of networks of specialised innovators.

Building upon previous empirical research, the chief aim of this paper is to argue that the role of large firms may have changed, but it is far from disappeared. It does so looking at the interplay of increasing knowledge specialization, the development of products of increasing complexity that perform a widening range of functionalities, and the emergence and diffusion of new design strategies for both products and organisations, namely modularity. The emergence of modularity as a product and organizational design strategy is clearly connected to recent trends in organisational design. Modularity would allow the decoupling of complex artefacts into simpler, self-contained modules. Each module would, at the extreme, become the sole business of a specialized trade. This paper builds upon the idea that there are cognitive limits to this process of modularisation: what kinds of problems firms solve, and how they solve them, set limits to the extent of division of labour among firms. We draw implications of such limits for both management and economic theory.

Our paper is organized as follows. Section 2 describes past and on-going changes in organizational specialization in the production of artefacts and the production of knowledge. Section 3 focuses on the distinction between artefacts and knowledge, and shows the cognitive limits to the extent to which knowledge and problem-solving activities can be modularised. Section 4 speculates about the implications of our past research for organizational sciences and economic theory. Section 5 concludes.

2. EVOLVING TECHNOLOGIES & ORGANIZATIONAL SPECIALIZATION

From interchangeable parts to modular networks

The recent growth of product modularity must be seen as part of the continuing interaction between changes in technology and in organizational specialization over the past 200 years. These are discussed in detail below and are summarized in Table 1, which shows that:

- certain major advances in technology have been key factors in changes in organizational specialization, sometimes leading to disintegration, and sometimes to integration;
- the degree of disintegration in the production of artefacts has always been greater than in the production of technological knowledge.

{Table 1 about here}

Adam Smith's pin factory is mainly a story about innovation in production processes. The conditions for the mechanization of repetitive manual operations emerged from the specialization of tasks within the factory. As anticipated by Smith, the design and building of these machines would become '… the business of a peculiar trade …'. This happened with the spread and the growing standardization of specific mechanical operations (e.g. spinning and weaving in textiles), which went hand in hand with the growth of a large demand for standardized goods. More generally, the provision of product components and parts becomes specialized businesses as they became standardized and inter-changeable. And the provision of mechanical inventions itself became a specialized trade, with the development of specialised intermediaries, namely, patent agents (Lamoureaux and Sokoloff, 1999) and consultant engineers (Saul, 1967; 1970). So, in those sectors where a large demand for homogeneous consumer goods developed, there also developed a division of labour between independent manufacturers, machine builders and mechanical inventors. This inter-firm specialization would not have been possible without continuing and largely craft-based improvements in the quality of the metals, and the accuracy with which they could be cut or shaped (Bernal, 1953).

However, a number of complementary radical innovations from the middle of the 19th century generated two trends that pushed toward increasing integration of innovative activities. Both have been documented by Chandler (1977; 1990), Mowery and Rosenberg (1991) and other scholars. The first is the emergence of mass production, in order to exploit the economies of scale and speed in production, and the reduced transport costs, both made possible by the availability of the new power sources (e.g. coal, and then electricity and oil) and better materials (e.g. high quality iron, then steel). Increasing size led to increasing functional specialization with the firm, and the need for co-ordinated planning between material purchase, production and marketing.

Second, advances in specialized mechanical, chemical and electrical knowledge opened up major new opportunities for product innovation, not only in machinery and parts, but also in consumer goods, transportation, materials and communications. The development of these new products required the integration of partly tacit knowledge across disciplines (e.g. purely mechanical products became electro-mechanical), and between the R&D and other functions within the firm, particularly manufacturing and marketing. Under these circumstances, integration has been more efficient than markets (Mowery, 1983). This form of organization of production and related knowledge became the dominant form in the 20th century.

However, in the last 20 years, new forces have surfaced that begin to modify this pattern. Products are becoming increasingly complex, embodying both an increasing number of subsystems and components, and a widening range of fields of specialized knowledge. This increasing product (or system) complexity is itself one consequence of increased specialization in knowledge production, which has resulted in both better understanding of cause-effect relations, and better and cheaper methods of experimentation. This in turn has reduced the costs of technological search, and thereby enabled greater complexity in terms of the number of components, parts or molecules that can be successfully embodied in a new product or service.

Increasing knowledge specialization and complexity challenges traditional ways of co-ordinating firms' activities. Specialization in knowledge production has increased the range of fields of knowledge that contribute to the design of each product. Compare what originally was the largely mechanical loom, with the many fields of specialized knowledge – electrical, aerodynamic, software, materials – that are now embodied in the contemporary design; or observe the contemporary automobile that must increasingly integrate plastic and other new materials, as well as electronic and software control systems.

The growing number of specialized fields that are embodied in increasingly complex products also leads to an increasing number of specialized professions and communities whose activities need to be monitored and co-ordinated to be competitive. Relatedly, firms designing these increasingly complex products have found it more difficult to master advances in all the fields embodied in them. Hence the growing importance of modular designs, where component interfaces are standardized, and interdependencies amongst components are decoupled. This, in principle, enables the outsourcing of design and production of components and subsystems, within the constraints of overall product (or system) architecture.

Opportunities have also emerged for further vertical disintegration between product design and manufacture, based on further technological convergence (i.e. in convergence, based on technical change, in specific production operations across firms, products or industries). Rosenberg (1963) has shown how specialized machine tool firms emerged in the 19th century, because advances in metal cutting and metal forming techniques led to technological convergence in operations that were common to a number of manufacturing processes (e.g. boring accurate circular holes in metal was common to the making of both small arms and sewing machines). The size of the market for such common operations therefore often became large enough to sustain the growth of small specialized firms designing and making the machines to perform them. Large manufacturing customers could therefore buy machines incorporating the latest improvements fed back from many users, and therefore superior to what they could do by themselves. In contemporary terms, designing and making such machines no longer gave large manufacturing firms a distinctive competitive advantage. Subsequently, similar mechanisms have been at work in such fields as control and measuring instruments, chemical process engineering, robots and applications software.

A third factor now modifying patterns of specialization is the impact of advances in ICT, reflected in reductions in the cost and increase in capacity of several orders of magnitude for storing, manipulating and transmitting information. These changes open options for more complex systems (through digitization), reduce the costs of experimentation (through simulation techniques) and allow greater disintegration (through lower costs of transmitting information) (Pavitt and Steinmueller, 2001; D'Adderio, 2001).

At first sight, these changes appear to point to a neatly specialized system for the production of innovations, with product and systems designers, their sub-contractors for components and subsystems, and their manufacturers, working together through arm's-length market relations. For example, Sturgeon (2002) has analyzed the rise of contract manufacturing in electronics: namely, firms that take over electronic product designs from other firms, and do the detailed engineering and manufacture. The technological convergence is based on increasing automation of routine operations (e.g. component insertion), and on the increasing use of standard software tools. He reports that contract manufacturing is also growing in other industries[1], and stresses the importance of the development of '… the modular production network, because distinct breaks in the value chain tend to form at points where information regarding product specifications can be highly formal....within functionally specialized value chain nodes activities tend to be highly integrated and based on tacit linkages. Between these nodes, however, linkages are achieved by the transfer of codified information.'

Sturgeon's 'modular' network is thus characterized by a specific pattern of division of labour, and implicitly assumes a similar pattern of division of knowledge. Each node (a firm) in the network should specialize on a specific, mono-functional, module. Each firm should carry out R&D on that module. An assembly company would be present, selecting modules on a competitive basis, and assembling them following the interfaces of the

[1] He lists apparel and footwear, toys, data processing, offshore oil drilling, home furnishings and lighting, semiconductor fabrication, food processing, automotive parts, brewing, enterprise networking and pharmaceuticals. In addition, Prencipe (1997) has shown increases in the outsourcing of production of aircraft engine components.

existing product architecture. The assembling company would maintain capabilities over the interfaces, and the assembling activities, but would consider each module as a 'black box'. Architectural and component-level knowledge and capabilities should be separated, the former being developed by the assembling company, the latter by the component suppliers. The very process of innovation could be modularised: each firm, focusing on a specific module, would be able to focus its learning and innovative efforts (Arora, Gambardella and Rullani, 1998). As pointed out by Sanchez and Mahoney (1996) and Radner (1992), since components' interfaces are not permitted to change within an intended period of time, a modular architecture would create an 'information structure' that smoothly co-ordinates decentralized design teams. In this way, the 'information structure' would also act as a 'compensation mechanism' that holds the systems together without the need to exert explicit managerial authority.

3. THE DIVISION OF LABOUR AND THE DIVISION OF KNOWLEDGE

We have argued in the past that it is highly dangerous to neglect the importance of the distinction between the properties of artefacts, the knowledge on which they are based, and the degree to which such knowledge can be transformed into information (Brusoni, Prencipe and Pavitt, 2001). It is one thing to co-ordinate the development and production of artefacts; and another thing altogether to co-ordinate the evolution of the underlying knowledge bases. Briefly stated, in a number of sectors, technologies and products have been shown to follow interconnected, yet different, dynamics (Brusoni and Prencipe, 2001). Detailed sectoral studies confirm that (some) firms within networks of vertically related companies maintain S&T capabilities over a set of fields wider than that justified by their in-house activities. Thus, 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. Similar results emerged from studies of highly innovative sectors, such as aero-engines (Prencipe, 1997), pharmaceuticals (Orsenigo, Pammolli and Riccaboni, 2001), telecommunications infrastructure (Davies, 1997), and hard disk drive (Chesbrough and Kusunoki, 2000). Similar evidence is emerging from detailed studies of traditional sectors such as chemical engineering (Brusoni, 2001), tyres (Acha and Brusoni, 2002), oil exploration (Acha, 2002) and the automotive industry (Takeishi, 2002).

The gap between firms' production and knowledge boundaries is 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, 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. Brusoni, Prencipe and Pavitt (2001) developed a simple framework that explains how firms reconcile this strategic dilemma, using networks of specialized suppliers of components and knowledge. In particular, they showed that the interaction of component- and technological-level interdependencies leads to the emergence of alternative organizational forms, which they named as decoupled (or modular) networks, tightly coupled networks (at the extreme, a vertically integrated firm), or loosely coupled networks.

{Figure 1 about here}

Each organizational form relies on a different mode of co-ordination. Modular networks would rely on market incentives, and the information structure defined by the modular product architecture. Tightly coupled networks would rely on the traditional advantages of hierarchies and ownership. A key characteristic of loosely coupled network organizations is the presence of a systems integrator firm that outsources detailed design and manufacturing to specialised suppliers while maintaining in-house concept design and systems integration capabilities to co-ordinate the work (R&D, design, and manufacturing) of suppliers. These networks may produce modular products, but are not themselves modular, as they are led by firms that maintain an 'integrated' knowledge base, even in the presence of a great deal of specialization at the functional level (e.g. manufacturing, distribution, etc.).

The functioning of markets and hierarchies as co-ordination devices has received quite a lot of attention. In the context of increasing knowledge specialization, and product complexity, new ways of co-ordinating activities are emerging, as well as new organizational forms: the notion of 'hybrid' organization (often evoked) hides more than it reveals. Our earlier research on organizational 'coupling' meant to provide more useful categories to study hybrid, yet long-lasting, ways of organizing the production of knowledge and artefacts. We proposed the concept of coupling for identifying them and that of systems integration to address the issue of how they are co-ordinated. The following section briefly summarise a specific case of a modular product (a chemical plant) developed by an organisation that is not itself modular. We use such case discussed at length elsewhere to ground our conclusive 'speculations'.

3.1. Toward modular networks? Some empirical observations.[2]

The organization of chemical engineering activities is often used as an example of highly modularized activity (Landau and Rosenberg, 1992; Rosenberg, 1998; Arora, Gambardella and Rullani, 1998). First, the artefact (i.e. the chemical plant) is made up of a huge number of 'modules' whose interconnections seem to be well understood. Indeed, different modules are likely to be produced by specialized suppliers, which produce according to specifications. No component is actually produced by the final users, or leading engineering designers. Second, the very discipline of chemical engineering developed out of the principle that all chemical processes can be designed by mixing and matching a finite number of unit operations and unit processes (Rosenberg, 1998). Third, the maturity of the technology (and other factors) has led most chemical firms to outsource their engineering services, particularly at the detailed engineering level. It seems that these dynamics well describe what Sturgeon (2002) called a 'modular network'.

Brusoni (2001, 2003) analyzed in detailed the project management strategies of chemical firms following the great outsourcing and downsizing wave which started in the mid

[2] This section builds upon Brusoni (2003), sections 3 and 4.

1980s. First, it is true that the maturity of the technology has led to a tight division of labour between chemical firms and Specialized Engineering Firms (SEFs) on the one side, and component suppliers on the other. A chemical plant is, overall, a modular product. But this is as far as the modularity argument goes. Indeed, while it is true that the discipline of chemical engineering was founded on the notion of mixing and matching unit operations, it is also true that increasing understanding of the dynamics and kinetics of the chemistry used led to the adoption of more general representations of how chemical processes 'happen'. In the 1960s, the 'transport phenomena' revolution (Furter, 1980) changed the way chemical engineers conceptualize chemical processes. Nowadays, all chemical processes are represented in terms of mass and energy balance equations that 'cut across' specific process steps, and unit operations. More interestingly, even at the engineering level, where plant modularity is a very common construction strategy, engineers commonly use search heuristics alternatives to increasing modularity. For example, 'telescoping' - i.e. the integration of different functions within a single module - is also quite common, and maybe leading to major changes in the way this industry works.

It is worth noting that chemical firms maintain capabilities on complex and critical process steps, such as reaction modelling, catalysis and catalysts, and separation processes. They do so in order to be able to act as problem solvers of last resort, a sort of central bank of capabilities. Chemical firms that have outsourced and downsized without maintaining in-house capabilities on critical process steps have become very 'poor clients' for SEFs, as they cannot specify what they need, nor can they intervene when problems occur. The most effective project management strategies are characterized by the integration of the design teams of both chemical firms and SEFs, rather than by the modular 'handing over' of a complete design package to a competitively selected supplier of engineering services (see Figure 2).

Brusoni and Prencipe (2001) argued that projects where contractors have full responsibility from the very early stages of project definition (with almost no input from the owner) are those exhibiting the worst overall performance. Figure 2 reports some performance indicators relative to cost growth (over the expected values), relative engineering and construction time (as a measure of the re-working 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). Furthermore, even the 'all operators' projects do not show outstanding results: they face increasing difficulties in defining the overall goals and technology requirements of their projects, because of the loss of experienced personnel. The best performers are the 'integrated' projects, where contractors are brought on board early and the lead is taken by whoever retains capabilities particularly relevant to the project. As discussed in Brusoni and Prencipe (2001), rather than tight division of labour, good project performance requires increasing integration (within projects) between operators and contractors. What was disintegrated on one side (in terms of in-house detail design capabilities) has to be re-integrated by an open and integrated management of projects. Operators have tried to compensate decreasing in-house capabilities (of a specific kind) by 'pulling up' contractors into a different type of design activities: more upfront design activities are now expected from SEFs, traditionally more involved in detailed engineering, construction and project management activities.

{Figure 2 about here}

But why this increasing 'integration' at the project level? Brusoni (2003) argued that the division (and modularization) of engineering labour is limited by the nature of engineering design as a problem-solving activity, rather than by the extent of the market per se. He decomposed engineering design activities into two 'modes' of problem-solving (analysis and synthesis), and then discussed their organizational implications. The aim of designers in 'synthesis mode' is to generate 'a system from its constituents' given different possible inputs and expected outputs. This is the stage when engineers aim at generating variations (figure 3). Engineers in 'synthesis mode' generate process alternatives (i.e. decomposition patterns) that are then evaluated in terms of the sub-problem trees of which they are constituted. This is why chemical firms that have reduced their direct involvement in overall engineering design activities, still maintain capabilities focused on the key components and process steps.

The aims of designers in 'analysis mode' are different. They need to check that all sub-problems within a given system can actually be solved in a consistent manner and all process stages deliver what they are expected to. This is the stage when engineers approach sub-problems in order to retain selectively those variations that generate solvable sub-problem trees (see figure 3). Engineers in 'analysis mode' explore specific sub-problems along a pre-defined (at synthesis level) set of interdependencies that impose limits on the degrees of freedom they can exploit.

{Figure 3 about here}

Although distinct, these two problem-solving modes cannot be perfectly separated in cognitive terms. Technological- and component-level factors determine the extent to which engineering labour can actually be divided. This is why chemical firms that have reduced their direct involvement in engineering design activities, need to set highly integrated and collaborative project environments: they need to access early on the detailed engineering capabilities maintained by the SEFs. Engineering design problem-solving is based upon the recursive exploration of hierarchically decomposed problems. Critical and technically difficult process steps require extensive detailed calculations and testing prior to the decision to freeze a design package. Also, uneven rates of change of the technologies (i.e. bodies of knowledge and practice) that engineers rely on determine salients that induce firms to integrate and develop in-house competencies to explore new search paths. These explorative activities entail a sequence of synthesis/analysis problem-solving that limits the extent of division of engineering labour.

This recursive process of analysis and synthesis limits the extent to which engineering labour can be modularised, and co-ordinated through the exchange of codified information. For example, co-locating design teams from different firms involved in the same project is a very common strategy. Organizational strategies have to consider the interaction between different types of engineering design and different modes of engineering problem-solving. Such an interaction sets limits to the emergence of truly modular networks, co-ordinated through markets and the exchange of codified information. Firms and corporate HQs are not replaced by markets, but by the temporary hierarchy defined within a specific project. Hence, the emergence of less-than-modular networks.

The wide capabilities that integrators maintain in-house allow them to solve problems in a co-ordinated manner, i.e. co-ordinating specialized suppliers of components and knowledge through 'authoritative' interventions. As stressed by Simon (1982) and more recently by Loasby (1999: 100), authority is not necessarily associated with formal hierarchies but rather with the willingness of the recipient to consider a specific 'communication' as 'authoritative'. In turn, this willingness derives from the acceptance of 'zones of indifference' whereby recipients reckon they have to rely on the capabilities of somebody else, somebody to whom they grant 'authority'. Chemical firms can work as 'problem-solvers of last resort' as long as they know much more than any one other organization involved in the design and engineering of a plant. SEFs appear therefore to be willing to accept operators' 'authority' whenever their capabilities do not allow them to solve a specific problem.[3] However, within a chemical engineering network, the complexity of the activities is such that authority flows up and down the hierarchy seamlessly, because no-one or no single organization can encompass all the bits of relevant knowledge needed (hence the success of the 'integrated' projects in figure 2). It is well known that different SEFs do maintain specialized capabilities on specific process steps, or types of catalysts. For example, historically M.W. Kellogg has maintained and developed capabilities focused on ethylene processes and high-pressure ammonia synthesis.

4. CO-ORDINATION IN THE MODULAR AGE: SOME IMPLICATIONS

This section highlights possible future developments of this line of research. We speculate along two lines. First, we have argued that the authority of systems integrators depends on their abilities to 'frame' problems, to simplify them identifying things that 'do not deserve to be pursued any further'. This type of problem-solving (i.e. synthesis) is not perfectly separable from the 'analysis' of specific sub-problems: alternative decomposition patterns can be assessed only in terms of the sub-problems they generate, and their solvability. Hence, the finding that system integrators maintain capabilities at both the architectural level and the component level (see also Prencipe, 1997; Davies, 1997). Section 4.1 builds upon this result to argue how it is 'organizationally possible' for some firms to extend their span of 'authoritative communications' beyond their boundaries, as defined by the ownership of assets. In so doing, we discuss the increasingly studied notion of the project-based firm (PBF).

[3] Contractual considerations also play a role. There are problems SEFs cannot solve without involving their clients because they need approval for decisions that may radically change the budget and/or the timetable.

Second, we have argued that chemical firms that have outsourced their detailed engineering capabilities still need them when they are solving problems in synthesis mode. Hence, the finding that SEFs are being involved more and more often in conceptual design activities, and the better performance of 'integrated' projects relatively to more arm's-length solutions, based on the transfer of a codified design package. Section 4.2 will focus on what this line of enquiry might contribute to economics research on firms' boundaries. Particular attention will be devoted to the incomplete contracts theory, and the problem of allocation of residual rights in the presence of unforeseen contingencies.

4.1. The span of authority: the project-based organisation.

The imperfections of the market system in the presence of uncertainty are well known, at least since the seminal works of March and Simon (1958) and Arrow (1974). However, counter arguments are not in short supply. See for example the literature on modularity that stresses how modular architectures define an information structure that holds together decentralised networks with no need for explicit authority (Sanchez and Mahoney, 1996; Arora. Gambardella and Rullani, 1998, Sturgeon, 2002). Our own fieldwork showed that external inputs are very useful when 'integrators' are still in synthesis mode. For example, consultants exist that provide not only tools and techniques to improve a firm's decision-making process, but also decisions. See, for example, the emergence of a specialised niche sector of engineering consultants that advice chemical firms on whether or not to sanction major capital projects, or how to change the proposed design package.

While we have argued that the case for 'modular networks' co-ordinated by markets through the exchange of codified information is overstated, we also believe that the case for hierarchies needs to be reconsidered in the light of new empirical evidence that highlights the emergence of new organizational forms. Thus, we discuss the role that 'projects' and project-based organizations play in enhancing our understanding of the role of firms in the modern economy.

Let us start by noting that the co-ordination of specialized knowledge ultimately resolves into the co-ordination of specialized communities. Communities are defined around

However, the engineers interviewed in the fieldwork stressed the high-level 'problem-solving' role played specific tasks, activities, or practices (Brown and Duguid, 2001) or specific problems, or proble-solving methods (Steinmueller, 2000). The former are called 'communities of practice'; the latter 'epistemic communities.' Members develop a sense of 'belonging' to their community, to the extent that individuals' loyalty toward the community may be stronger than that to the 'organization'. Kogut and Zander (1996) argued that firms exist in order to provide one common 'identity' to their members, and that firms are much better than markets in providing resolution to conflicting loyalties. If by 'identity' we mean a 'common closure' to specialized learning processes, little room for disagreement is left. However, the key point overlooked by Kogut and Zander is that such organizational 'identity' need not be defined once and for all. In an innovative environment, this would hamper the capabilities to perceive and exploit new opportunities. In organizational terms, the case for 'hierarchy' is overstated. The approach we adopt here stresses that it is not a matter of identity, but of diverse *identities* that need to be – temporarily-reconciled.

This point is of fundamental importance in an innovative context. The interaction of heterogeneous communities is a vital source of variety, of new ideas, of new problems and new solutions. At the same time though, occupational groups can also resist change due to their epistemic and cognitive differences (von Meier, 1999). [4] Brown and Duguid (2001), like Langlois and Cosgel (1993) and Kogut and Zander (1996), conclude their analysis arguing that this type of 'interpretative' co-ordination is 'often better achieved within the structure of the firm than in the marketplace' (p. 209). But they really do not explain why. We think that by considering more closely how firms organize their actual engineering development activities, we can answer this question.

The key point to stress here is that firms in a variety of sectors operate on a project basis. A project is 'a temporary endeavour undertaken to create a unique product or service' (PMI 1996). A project is basically a contract, or rather a bundle of contracts, that specify duties, responsibilities and rewards of the firms involved in, for example, designing and building a chemical plant. To continue with our chemical engineering example, a project is defined around a design package (i.e. the output of engineers in 'synthesis mode'). The design package would define the key parameters of the plant to be built (e.g. capacity, main products and by-products, location, etc.). This design package provides a 'common

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by the operators' engineering units.

closure' to all the communities involved in the project, identifies the key technological and organizational interdependencies, set a timetable, allocate responsibilities. It is the result of the 'negotiation' undertaken between the various communities that coexist within a firm at all times. At the same time, the project is a 'temporary' endeavour. While providing, in a sense, a common identity to all the communities involved in the project, such an identity is going to disappear once the project is over.

We think it is no accident that the literature on project-based organizations (Gann and Salter, 1998) is developing as fast as that on communities and specialized knowledge. It is unfortunate that, so far, they have remained separated. The literature on project-based firms (PBFs) identifies these firms as characterized by the prevalence of project activities (as opposed to, for example, functions); their involvement in the design and production of customized products and services; and their involvement in wide coalitions of companies along the value chain (Gann and Salter, 1998: 450). Figure 4 describes how projects operate as 'gates' between the firm and the external environment. At the same time, this figure does capture the pivotal role played by in-house R&D and technical support units, and senior management.

{Figure 4 about here}

The concept of PBF is similar to that of 'adhocracy' proposed by Mintzberg (1989). However, the PBFs literature highlights that projects are becoming an increasingly diffused organizational strategy in a wide, and widening, range of sectors, spanning from traditional manufacturing to innovative, knowledge-intensive service industries. Projects seem to us a rather effective tool through which firms can reconcile the identities of the communities that interact within, and across, them. In a fast-changing environment, it is important that the diversity of identities is maintained; hence the importance of the 'temporary' dimension of project-based activities. In a competitive environment, it is also important to be able to bring specialized and dispersed learning processes to a 'common closure', and implement the selected solution; hence, the importance of projects as contracts that set duties, responsibilities and rewards on the basis of, for example, a design package. This idea of a 'temporary' identity clearly builds upon the notion of routines as

[4] We are grateful to Eugenia Cacciatori for making us note this point, and the work of von Meier.

'truces' (Nelson and Winter, 1982) and that of 'quasi resolution of conflict' (Cyert and March, 1963).

Projects appear to us as bundles of incomplete contracts with which firms prepare to unforeseen contingencies and opportunities. Projects enable firms to tie in 'networks of practice' (Brown and Duguid, 2001). Within projects, loosely related communities interact, achieving a temporary common identity. Once the project is terminated, the loose network of practice that had developed is disbanded. The management literature is quite rich in examples that stress how difficult it is to transfer lessons from project to project (e.g. Prencipe and Tell, 2001). The disappearance of the network of practice formed within the project might well explain why it is so difficult for project-based knowledge to leak into the next project. The context within which communication was possible is just not there anymore. Also, this line of reasoning extends the point we made in previous research on loosely coupled networks, co-ordinated by firms that 'know more than they make'. They do so because systems-integrating firms need to be plugged into a variety of communities of practice. They need to be linked to these communities to receive useful inputs at conceptual design stage, and to be able to select partners once the design package is frozen and the project set up around it.

4.2. Implications for economic theory

As argued by Langlois (2002), in the property rights tradition, the theory of the firm is largely 'a theory of the coalescence of property rights' (p. 29). This approach focuses on 'the incentives aspects of property'. One strand of this approach sees ownership as 'the equivalent to a claim on residual income' (ibid.). This is the approach of Alchian and Demsetz (1972), who focuses on the externalities problem generated by team production that leads to 'the coalescence of property into one set of hands' (ibid.). A second strand, initiated by the work of Hart (1989) sees ownership 'as involving residual rights of control', rather than residual income (ibid.). Either way, efficiency considerations would drive the process of reallocation of property rights.

However, uncertainty and specialized knowledge also play a role in determining the modularisation or coalescence of property rights. Langlois (2002), Loasby (1976; 1999) and Foss and Foss (2002) approach the incomplete contracts literature turning upside down the thrust of the discussion. They argue that the incompleteness of contracts is not of interest only (nor mainly) because, for instance, it causes ‘hold up’ problems, but also (and mainly) because of the learning opportunities these contracts open up to firms that face a truly uncertain environment. As Loasby (1999) put it, the open-endedness of contracts leaves room for future contracts to accommodate unforeseen (and unforeseeable) circumstances. The fact that contracts are incomplete is not a problem. It is an opportunity.[5] This point brings to mind mainstream work on property rights (e.g. Klein, 1992). As recognized by, for instance, Holmström and Roberts (1998), economic theory identifies the boundaries of the firm ‘with the ownership of assets, but in the real world, control over assets is a more subtle matter’ (p. 84). Within a property rights framework, they point out that ‘contractual assets’ can be created to serve the same purposes that theory assigns to ownership. They call these contractual assets ‘governance contracts’, and they are ‘powerful vehicles for regulating markets’ (p. 85). The chief effect of this specific type of contract is to ‘place firms at the center of a network of relationship, rather than as owners of a clearly defined set of capital assets’ (ibid.).

Their position is quite interesting in a number of ways. First of all, it is just reassuring to see that the issues proposed by Richardson in his seminal work are still pertinent to economic analysis (‘Firms are not islands but are linked together in patterns of co-operation and affiliation’, 1972: 895; but see also his earlier 1960 book). Second, in a rather abstract manner they raise problems that the more empirically-oriented literature on which this paper largely relies has also addressed, and partially solved. Two issues are worth mentioning here. First of all, firms within this ‘network of relationships’ (Holmström and Roberts, 1998: 85) are not all alike. Some firms will be more central than others, and play different roles within these networks. This observation is quite pertinent to our discussion of, for example, systems-integrating firms. Why some firms become central nodes, and how, while others do not, is an interesting question. We think that some research on modularity can help explain this problem. The concept of authority as developed above, and its linkages to the notion of ‘judgement’ and ‘capabilities’ all help in addressing these questions.

[5] Within more mainstream terrain, Becker and Murphy (1992) develop a formal model that is quite close to this discussion using the notion of ‘specialized knowledge’ and modelling the vertical relationship between

Secondly, networks differ in a number of ways, and the examples that Holmström and Robert put forward are actually examples of extremely heterogeneous network structures (e.g. biotechnology, software, steel). Research on modularity has put forward a variety of organizational forms that are associated with the diffusion of modular products (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Brusoni, Prencipe and Pavitt, 2001; Helfat and Eisenhardt, 2002; Sturgeon, 2002). For example, a more precise analysis of the technological and component-level interdependencies that firms need to address when designing products and processes might explain the emergence of alternative network forms.

Moreover, like all contracts, even the governance contracts that Holmström and Roberts (1998) discuss, are likely to be incomplete. This creates all the problems (and opportunities) that the literature on property rights and incomplete contracts focuses on. It is interesting to analyze what the criteria are that lead to the allocation of residual rights in an incomplete governance contracts setting. Again, we think that this sort of question can be answered by looking at recent studies that focus on innovation, modularity and the boundaries of the firm. For example, in our fieldwork, and related industry studies, systems integrators appear as the holders of the residual right to solve unforseen problems that emerge as the design problem unfolds. What enables them to do so is the wide (and widening) range of scientific and technological capabilities they maintain in-house. More generally, we contend that the distinction between knowledge and artefacts, and the related distinction between the knowledge and production boundaries of the firm can help make sense of the subtleties and fuzziness of the organizations we observe in the real world. In particular, a number of useful lessons can be learnt when analyzing how firms design projects, how they select partners, and what specific contractual mechanisms are put in place. We do not know enough, for example, about how different methods of 'pricing' engineering and construction services impact the project performance.

Relatedly, it is worth noting one fundamental point that the economic theory should contribute to our understanding of modularity. The organizational and management literature we have relied on analyses firms and communities as 'learning environments'. Firms and organizations are not just problem-solving devices. They also embody incentive

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different types of agents. Jensen and Meckling (1992) also touch upon these issues in an incomplete and monitoring structures. We do not know much about this. The key working assumption we have maintained is that the main problem is understanding how firms develop and access the capabilities necessary to conceive, design, build and market a new product. If the capabilities are in place, co-ordination is about solving problems of 'cognitive dissonance'. But opportunism does not play a big role in this picture. This is at odds with much work of firms and organizations, and needs to be taken into account.

5. CONCLUSIONS AND SPECULATIONS

This paper started trying to put modularity in its historical context. We have argued that modularity and organizational disintegration are the latest cognitive and organizational responses to increasing systemic and cognitive specialization and complexity. As in earlier responses, disintegration is stronger in the production of artefacts than in the production of knowledge. Co-ordination and systems integration are necessary to establish product-system architecture, and to integrate both complex systems and fast-changing and partly tacit knowledge. As a consequence, we have discussed the notion of authority that is based upon the capabilities of systems integrating firms to solve complex problems, organize labour around the proposed solutions, and modify such an organization, should the need emerge.

On a theoretical note, the distinction between knowledge and product-level dynamics has important implications for management and economics. Regarding the former, we have argued in the past that modularity at the artefact level does not necessarily lead to modularity at the level of the organization, or its underlying knowledge bases. We have argued here that the emergence of modular networks is limited by the very nature of the social cognitive processes that underpin firms' activities (e.g. the links between analysis and synthesis). Recent research on the dynamics of communities of practice and project-based organizations seems to us to open promising avenues to analyze and understand the relationship between cognitive processes and new organizational forms without 'black-boxing' them into the hollow concept of 'hybrid organizational forms'.

contracts framework, when they talk about 'specific and general knowledge'.

Regarding economics, we think research on modularity might have useful implications for economists interested in understanding firms, the rationale for their existence, and their boundaries. We have speculated that by looking in some detail at how firms actually organise their high-level problem-solving activities, interesting links can be built between research on modularity and incomplete contracts theory. In so doing, it is possible to address issues related to how firms design 'governance contracts' (Holmström and Roberts, 1998) that put them at the centre of dense networks of relationships. We think it might be useful to link the notion of governance contract to that of 'project', and that insights can be gained by looking at the recent innovation and project management literature that focuses on 'project-based firms'. In this way, we think that it is possible to address issues relating to:

- the 'shape' of these networks (e.g. modular, tightly coupled or loosely coupled)
- what roles different firms play in these networks (e.g. specialized suppliers vs. systems integrators)
- what functions are played by these networks (e.g. provide heterogeneous communities with a temporary common identity)
- how residual rights of control are allocated when contracts are incomplete.

Paying attention to the distinction between knowledge and product dynamics is also useful to make sense of recent changes in the international division of labour. We may speculate that increasing international outsourcing of manufacturing and design facilities toward low cost countries reflects a major shift in the opportunities for major technical changes from the processing of materials into products, towards the processing of information into services. As a consequence, we argue that the locus of competition through innovation in leading companies could shift from discrete physical product and process innovations associated with manufacturing, to innovations in the design, development, integration and marketing of increasingly complex products and systems.

As foreseen by Drucker (2001)[6], this could lead to an increased – but still incomplete - disintegration between systems integration firms and manufacturing firms. It could also re-inforce the shift of manufacturing towards certain lower-wage countries. However, the high-skilled 'services' in which the high-wage countries specialize would not be

[6] See his contrasting visions of the futures of GM and Toyota (pp. 18-19)

‘‘immaterial’’ in the conventional sense. They would comprise high-tech machines (processing information rather than materials), mastery of the knowledge underlying manufacturing, and a capacity for designing, integrating and supporting complex physical systems, including simulations and modelling products and processes, production and logistic operations, monitoring and control, and customer support: in other words, the skilled activities that manufacturing firms undertake, except manufacturing itself. The fact that most of these activities are defined as ‘‘services’’ often confuses rather than clarifies.

In this sense, firms specializing in systems design and integration are not post-industrial. They are instead the prolongation of the industrial system into a period of growing specialization and complexity, and of growing capacities to store, transmit and manipulate information. High wage countries may indeed find themselves specializing increasingly on ‘‘services’’, not as an alternative to manufacturing activities but as the skill-intensive components within them. The Visible Hand of manufacturing will not become invisible (Langlois, 2001), but continue to exploit economies of physical scale, speed and scope. At the same time, the Visible Brain of systems integration could become the dominant form of business organization in the world’s advanced countries.

Table 1

Modularity in the context of increasing specialization in technology & complexity in artefacts

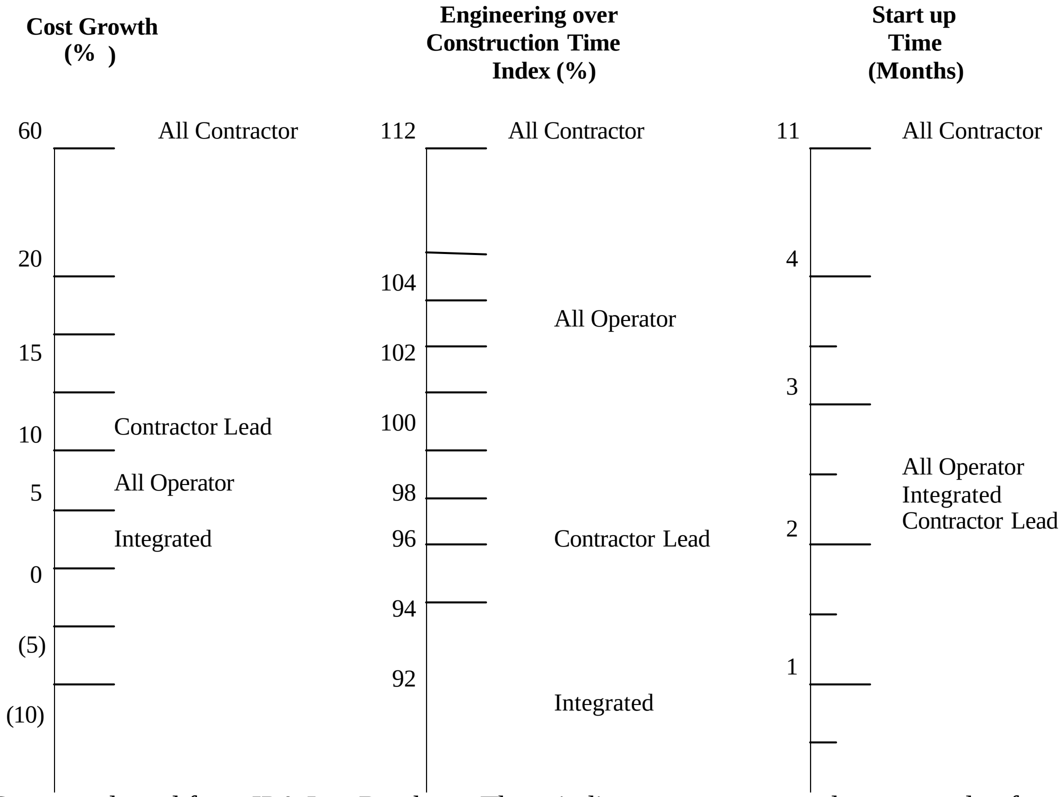
Changes in Technology	**Implications for Firms' Management**	**Organizational integration/disintegration**	
		Manufacture	**Knowledge**
Improvements in metal cutting and shaping	Interchangeable parts	Vertical *disintegration*	Vertical *disintegration*
Energy (coal) Materials (iron and steel)	Mass production of standard commodities	Specialization & *integration* of purchasing, production, marketing Vertical *disintegration* in capital goods	*In house* development of specialized skills *In-house* knowledge of design, & operation of capital goods
Organic chemistry Physics	Synthetic products Electrical & electronic products	*Integration* of product design, manufacture & marketing	Growth of *in-house* R&D as dominant source of innovation
Various (e.g. metal cutting, chemistry, computing, ITC)	Technological convergence in segments of production	Partial vertical *disintegration* in production segments (e.g. machine tools, continuous processes & instrumentation, CAD, robots, applications software)	*In-house* knowledge of design, & operation of producers'goods
Increasing product complexity (more components, sub-systems, and bodies of knowledge) ICT	**Modular product designs**	Vertical *disintegration* in design & production of product components and sub-systems.	*In house* knowledge of design, & operation of subsystems & components
ICT	Technological convergence in manufacturing (e.g. electronic products)	Vertical *disintegration* in production	*In house* competence in product (systems) design & integration

Figure 1.
Organizational coupling and different modes of co-ordination 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 **Co-ordination via 'markets'**	Loosely Coupled Automotive industry Outsource production and detail engineering. Both contract and in-house R&D **Co-ordination via 'authority'**
	Uneven	Loosely Coupled Hard disk drive industry Outsource production and detail engineering. Both contract and in-house R&D **Co-ordination via 'authority'**	Tightly Coupled Mobile phone systems Design, production and R&D in-house **Co-ordination via 'ownership'**

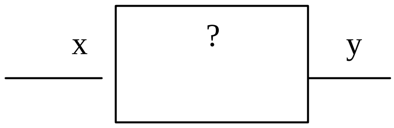
Source: adapted from Brusoni, Prencipe and Pavitt (2001).

Figure 2.
Division of labour and project performance



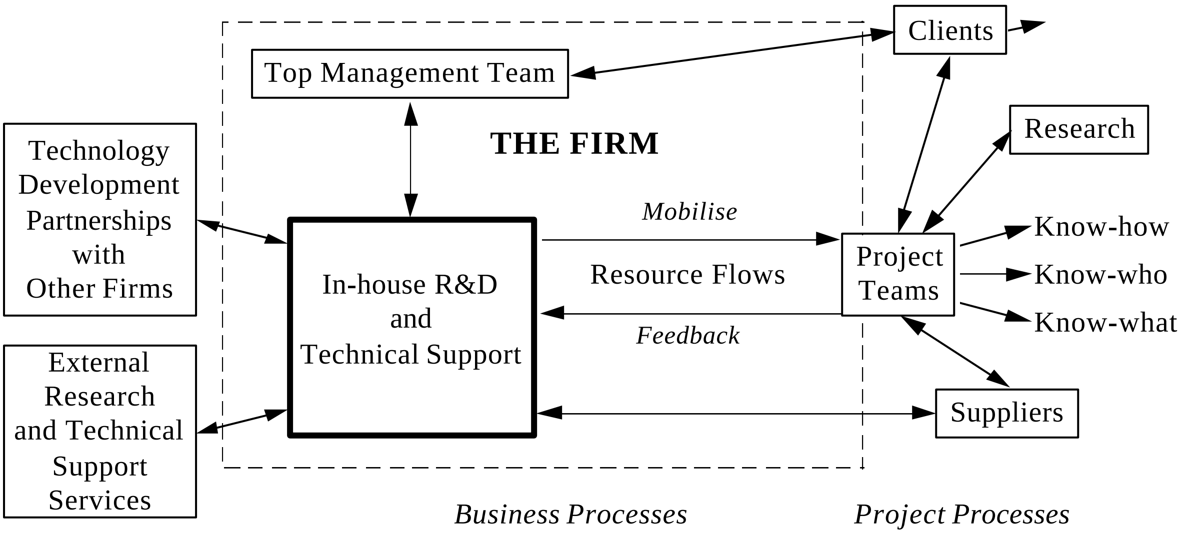
Source: adapted from IPA Inc. Database. These indicators are computed on a sample of more than 3000 projects executed worldwide, between 1985 and 1997. Data are normalized by project size and degree of technological novelty.

Figure 3.
Scheme of tasks for analysis and synthesis

	Analysis	**Synthesis**
		
Given	Inputs and system	Inputs and outputs
Wanted	Functional model and output	System design
Tasks	Decomposition, modelling, simulation	Identification of key interdependencies, evaluation, optimization, control

Source: adapted from Brusoni (2001)

Figure 4.
The project-based organization.



Source: Gann and Salter (1998)

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