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Authority in the Age of Modularity

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Abstract
This paper builds upon on-going research into the organisational implications of ‘modularity’. Advocates of modularity argue that the Invisible Hand of markets is reaching activities previously controlled through the Visible Hand of hierarchies. This paper argues that there are cognitive limits to the extent of division of labour: what kinds of problems firms solve, and how they solve them, set limits to the extent of division of labour, irrespective of the extent of the market. This paper analyses the cognitive limits to the division of labour relying on an in-depth case study of engineering design activities. On this basis, this paper explains why co-ordinating increasingly specialised bodies of knowledge, and increasingly distributed learning processes, requires the presence of knowledge integrating firms even in the presence of modular products. Such firms, relying on their wide in-house scientific and technological capabilities, have the 'authority' to identify, propose, and implement solutions to complex problems. In so doing, they co-ordinate networks of suppliers of both components and specialised competencies.

1. INTRODUCTION

Recent research on modularity has greatly improved our understanding of the relationship between what firms do, how they do it, and what they need to know in order to do it. This literature has provided both theoretical insights and empirical foundations to much writing about emerging organisational models for the new, globalised, post-industrial and service intensive economy. And it has also highlighted that contentious questions such as ‘What are firms? Why do they exist? What are their boundaries?’ persist. Indeed, the literature still presents contrasting, and even contradictory views of what role is left to the authority of the corporate headquarters in the global village. Some scholars have argued that modularity impacts not only the way firms design and manufacture their products, but also on firms’ boundaries (through changes in transaction costs), and corporate functions (through changes in incentives and monitoring systems). As a consequence, the very existence of ‘Chandlerian’ firms would be challenged by the emergence of modularity (Schilling and Steensma, 2001). Others contend that while the Visible Hand of a centralised headquarters may be losing its grip on day-to-day operational tasks, e.g. components manufacturing, the Invisible Brain of large and densely connected firms plays a fundamental role in coordinating knowledge intensive activities, e.g. engineering design. In other words, some firms ‘know more than they do’ in that they are able to co-ordinate loosely coupled networks of suppliers of both components and specialised knowledge (Brusoni, Prencipe and Pavitt, 2001).

This paper extends this work exploring the cognitive foundations of co-ordination and authority within loosely coupled networks of vertically related firms. Penrose’s influential work built upon the definition of the ‘firm’ as a collection of resources bound together in an administrative framework, the boundaries of which are determined by the ‘area of administrative co-ordination’ and ‘authoritative communication’ (Penrose, 1959, XI). Implicitly, it was (and largely still is) assumed that such an area of administrative co-ordination, within which authoritative communications can take place, is determined by direct ownership of the ‘means of production’. This paper starts from the observation that the relationship between ‘authority’ and ‘ownership’ is complicated by the globalisation of manufacturing activities, and increasing knowledge specialisation (which, in turn, leads to the development of products of increasing complexity that perform a widening range of functionalities).

Understanding authority as a co-ordination device is of paramount importance for both practical and theoretical reasons. Firstly, in the context of increasingly globalised markets, ever more complex supply chains, and international manufacturing networks, corporate decision-making processes involve more and more actors, variables and criteria which lead to less and less transparency about who is deciding what, and on what basis. Secondly, and relatedly, the notion of ‘means of production’ is less and less to do with hardware, and more and more to do with information and specialised knowledge. Management tasks increasingly involve the monitoring, control and co-ordination of a widening range of useful scientific and technological disciplines that are embodied in products of increasing complexity, in terms of components and functionalities.

Modularity, as a product and organisational design strategy, provides a possible first approach to understand ‘authority’ in modern economies. Modularity allows the decoupling of complex artefacts into less complex, self-contained modules. Each module, at the extreme, could become the sole business of a specialist firm, which would have 'authority' over the specific module on which it focuses. This paper argues 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. The cognitive limits to the division of labour are explored through an in-depth case study on engineering problem solving activities.

This paper is organised as follows. Section 2 describes recent changes in the division and organisation of innovative labour. Section 3 reports on the empirical data used in this study, the methodology, and the main empirical results that focus on the distinction between division of labour and division of knowledge. Section 4 elaborates on the empirical results, discussing the concept of authority in the context of increasing knowledge specialisation and product complexity. Section 5 concludes.

2. THE DIVISION OF LABOUR AND THE DIVISION OF KNOWLEDGE

In the last 20 years, a number of forces have surfaced that challenge the role of the large, centralised, corporate R&D unit as the key engine of innovation. Information and Communication Technologies (ICTs) are often pinpointed as the key factor that is making it possible to abandon the traditional innovation strategy built upon the in-house R&D unit. Pushed by the emergence of new markets, shorter life cycles, and increasing product complexity firms will increasingly use ICTs

For example, Sturgeon (2002) has analysed the rise of contract manufacturing in electronics: namely, firms that take over electronic product design 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, 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 2002: 455)

The case of contract manufacturing in electronics is said to exemplify a 'new' way of organising business on a global scale, leading to a neatly specialised system for the production of innovations, with product and systems designers, their components and subsystems sub-contractors, and their manufacturers, working together through arm's-length market relationships. Schilling and Steensma (2001) provided evidence of the diffusion of modularity as an organisational strategy in a number of industries. Instead of relying on case studies, they designed and analysed a huge database of US firms to substantiate statistically the claim that firms are increasingly adopting a modular organisation, to identify those industries in which modularity is more common, and thus explain what factors lead to the adoption of a modular organisational form.

Others have focused on modularity as an innovation strategy. The very process of innovation could be modularised: each firm, focusing on a specific module, would be able to specialise in its learning and innovative efforts (Arora, Gambardella and Rullani, 1998).

This is, in a sense, the fundamental distinction between 'interchangeable parts' and modularity. The former largely represented a product design strategy that greatly increased the productivity of American manufacturers, and enhanced the reliability of their products (e.g. machine tools, fire arms). The latter is proposed as an overarching business model that has profound implications not only on how firms *do* things, but also on how firms organise to *change* things. For example, Arora and Gambardella (1994) talk about the 'new technology of technical change' enabled by the diffusion of ICTs (simulation software for design purposes in particular), and the process of knowledge codification in general and abstract categories - also enabled by the diffusion of ICT tools.

Processes of knowledge codification seem to be pivotal in explaining the changing organisation of innovative labour. For example, as long as it is the case that, as Sturgeon (2002) put it, 'linkages are achieved by the transfer of codified information' very little room is left for the traditional advantages of communication enabled by joint ownership (Arrow, 1974). Ownership is not the bond that makes a collection of functional units into an organised entity (i.e. a firm). Such a bond is not needed, some argue, because increasingly modularised and codified knowledge (embodied in modular components) and the transfer of codified information would be enough to achieve coordination. In other words, as pointed out by Sanchez and Mahoney (1996) building on Radner (1992), since component' interfaces are not permitted to change within a certain period of time, a modular architecture would create an 'information structure' that smoothly co-ordinates decentralised design teams. Thus, the 'information structure' would also act as a 'compensation mechanism' that holds the systems together without the need to exert explicit managerial authority.

However, dismissing the role played by explicit authoritative relations overlooks 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. In other words, it is one thing to coordinate the development and production of artefacts and quite another to coordinate the evolution of the underlying knowledge bases. To put it briefly, past research has highlighted that, in a number of sectors, technologies and products have been shown to follow interconnected, yet different, dynamics (Brusoni and Prencipe, 2001).[1] 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 explained by their in house activities. For example, 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 typically their product range has narrowed. Similar results emerged from studies of highly innovative sectors, such as aero-engines (Prencipe, 1997), telecommunications infrastructure (Davies, 1997), and hard disk drives (Chesbrough and Kusunoki, 2000). Evidence is also emerging from detailed studies of traditional sectors such as chemical engineering (Brusoni, 2001), tyres (Acha and Brusoni, 2002), oil exploration (Acha, 2002) and automotives (Takeishi, 2002).

The important distinction between the division of labour and knowledge is not generally captured by the modularity literature, which focuses on how firms that adopt a modular product design strategy can reorganise their supply chain, their own internal structure, and

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[1] In this paper, 'technologies' are not defined as hardware, but as bodies of scientific and technological 'knowledge' (Pavitt, 1998).

their new product development strategies. In other words, the emphasis falls squarely on what firms *do*. What they *know*, that is to say the capabilities they require to adopt a modular product design strategy, is not given specific attention (e.g. Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; 2000).

Brusoni and Prencipe (2001) first highlighted the fact that the adoption of a modular product design strategy does not necessarily lead to the adoption of a modular organisation, or to the modularisation of the firm's knowledge base. They introduced the idea that a gap might exist between firms' production and knowledge boundaries – this gap being the result of firms' 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 buy. But, on the other hand, firms' competitive positions may depend on their ability to introduce radical product and component innovations by building on in-house technological capabilities, i.e., they make. Brusoni, Prencipe and Pavitt (2001) developed a simple framework that explains how firms' reconcile this dilemma, using networks of specialised suppliers of components and knowledge. They emphasise the coordinating role played by 'systems integrating' firms, which rely on wide networks of suppliers of both specialised knowledge and components, while still maintaining wide (and widening) technological capabilities in most aspects of their value chain. While that paper focused on the organisational implications of the distinction between the division of labour and that of knowledge, the next section in this paper explores the cognitive foundations for that distinction, looking at how firms 'solve' complex problems.

3. TOWARD MODULAR NETWORKS? SOME EMPIRICAL OBSERVATIONS.

3.1. Data and Methodology

The organisation of chemical engineering activities is often used as an example of highly modularised 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 (e.g. reactor vessels, distillation columns, etc.) are likely to be produced by specialised suppliers, according to specifications. No components are produced by either the final user, or the leading engineering designers. Second, the very discipline of chemical engineering developed on 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) have led most chemical firms to outsource their engineering services, particularly at the detailed engineering level (Brusoni, 2001). It seems that these dynamics well describe what Sturgeon (2002) called a 'modular network'.

This paper draws on data collected during a three-year field study of the organisation of chemical engineering design activities in the UK-based chemical industry. The study was conducted in collaboration with other researchers involved in industry studies as part of a larger research centre[2] designed to explore, among other things, the distinction between the knowledge and production boundaries of firms that develop complex products like chemical plants, but also aircraft engines, flight simulators, mobile phone systems. While

[2] CoPS, Complex Products and Systems, SPRU, University of Sussex, UK.

the results of this study can stand alone, comparative research, and the combined use of both qualitative and quantitative evidence, has greatly contributed to establishing solid construct validity (Eisenhardt, 1989; Yin, 1994). The joint comparative work is described in Brusoni and Prencipe (2001) and Brusoni, Prencipe, and Pavitt (2001). This current study is based upon a multiple case research strategy. In methodological terms, an embedded design strategy was adopted as *firm* level analysis was performed in order to reach conclusions related to the dynamics of the division of labour at the *network* level. The network studied here is that constituted by the firms that interact to conceive, design, and engineer a chemical plant.

Three distinct types of data/information were employed to establish construct validity (Yin, 1994). Multiple data sources enabled stronger substantiation of constructs through triangulation of evidence across cases. The first type of information was gathered from a systematic review of the technical literature, trade publications, specialised engineering journals, company' annual reports and company publications. These data provided background information and an overall picture of the sectors analysed.

The second type of information used in the research is quantitative. Independent Project Analysis, Inc. (IPA, from here on) provided results drawn from a unique proprietary data set encompassing project-level data on over three thousand chemical projects (larger than US$5m) executed world-wide between 1985 and 1997. The data come from projects throughout the chemical industry but 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 organisational practices that impinge upon each project stage. Further, the data discussed here are normalised 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 analyse to evaluate the effects of changing patterns of division of labour across firms at project level.

The third type of information was derived from interviews. A set of 40 interviews was carried out. Chemical engineers from 14 companies, and four industry experts were interviewed. Background evidence was obtained from interviews with chemical engineers working for design software vendors and specialist consultants. The length of the interviews was between one and three hours. The interviewees were all senior people, including Vice Presidents of Technology, Technical Directors of Advanced Engineering Departments, Chief Process Engineers, and Head of Design Technology. All were either actively involved or had been involved in the past in design activities.

Data from these interviews were elaborated to produce case histories of the companies in the study. Qualitative insights provided by interviewees proved to be fundamental to an understanding of the knowledge requirements underlying the patterns of division of labour described by the quantitative data. This stage enabled the identification and evaluation of patterns as they emerged from "within-case" (Eisenhardt, 1989: 540). The cases were then cross-compared both within and between each layer of the network. As a multiple case research design was followed, a strategy of replication in multiple empirical settings was adopted in order to establish external validity (Yin, 1994).

3.2. The changing division of engineering labour in the chemical industry

The project management strategies of chemical firms after the great wave of outsourcing and downsizing that began in the mid 1980s, were studied in detail. Since the 1980s, large chemical firms have both downsized their engineering units dramatically and reduced the extent of their involvement in engineering activities. Common explanations for downsizing and outsourcing stress the role played by cost considerations in driving firms' organisational strategies. However, it is also necessary to consider those factors that have enabled firms to become leaner and at the same time maintain adequate standards in terms of product quality and safety. As argued in Prencipe (1997) and Brusoni and Prencipe (2001), when complex products are considered, the final assembly of the artefact is more than the mere mixing and matching of components. CoPS may exhibit emerging properties. Accordingly, one has to consider not only what factors have pushed firms towards downsizing and outsourcing, but also the factors that have enabled them to do it without, or at least minimising, losses in terms of technological and economic effectiveness.

Brusoni and Prencipe (2001) discuss both sets of factors by comparing the cases of aero-engines and chemical engineering: this section focuses only on the latter. The first set of driving forces has been labelled pushers, as they push chemical companies to hive off large chunks of activities related to design and development. In economic terms, pushers give firms the incentives to reduce their involvement in the design and construction chain and to increase their reliance on the services of specialist suppliers. The other set of driving forces is the enablers. Enablers directly affect the nature of engineering design activities as they provide the opportunity for firms to reduce their direct involvement in design and construction, while maintaining adequate standards of safety, and technical and economic performance. Enablers derive from the underlying knowledge base that constrain but make it possible for firms to react to the incentives they face.

In the case of chemical engineering activities, enabling factors involve the development of new design tools; the experience and expertise accumulated by both operators and contractors; and the maturity of the knowledge base; while pushers include the role played by increasing costs of development, construction and retrofitting; the infrequency of new construction in the OECD countries; the pressure from developing countries to use local engineering centres; and the advantages of specialisation at the detailed engineering level. In methodological terms, a list of factors derived from secondary sources (trade and academic literature) and pilot interviews was discussed with the interviewees. The interviewees ranked these factors in terms of importance and validated the distinction between enablers and pushers. Technical maturity on the one side and the advantages of specialisation at the detailed engineering level on the other were overwhelmingly pinpointed as the key factors driving change in firms' specialisation (see Table 1).

{table 1 about here}

Not only have operators reduced the number of chemical engineers they employ (i.e. they have downsized their engineering units), they have also reduced the scope of engineering activities conducted in-house (i.e. they have outsourced their engineering activities). IPA has developed a proprietary database to analyse the evolution of engineering activities in the chemical industry at the level of a specific project. Its database describes the evolution of operators' capital project capabilities, ranging from conceptual design to plant commissioning.[3] Based on this data, figure 1 shows a clear trend toward the reduction of

[3] IPA made available part of a database of projects carried out in the chemical industry world-wide in the period 1985-1997. This captures information on more than three thousand chemical projects (larger than $US 5 million) executed worldwide. The data have been normalised by project size and degree of technical

operators' involvement in detailed engineering. As confirmed by all the interviewees (without exception), such a trend cuts across the whole industry: operators have identified detailed engineering as a non-core activity that can be easily bought in when needed.

{Figure 1 about here}

The UK Chemical Industries Association (CIA) annual survey provides some evidence about the extent of involvement of contractors in capital projects broken down by type of activity. Table 2 presents the results of the 1990 survey. On average, operators outsource77% of all project activities to contractors and suppliers. Not surprisingly, activities related to the actual construction of the plant are those most likely to be managed by contractors (i.e. on-site fabrication and erection, mechanical and electrical installation, support buildings). Engineering is carried out mainly by contractors (60%), while design and project management is still the stronghold of operators' engineering units. Only 40% of design and project management was outsourced in 1990. Although the CIA survey does not allow changes to be traced over time [4], throughout the 1990s contractors' involvement in project management activities as well as design has increased.

{Table 2 about here}

But this is not a sufficient base from which to argue that the relationship between chemical firms and chemical engineering contractors has become increasingly modular over the years. Even though specialisation seems to prevail in terms of the range of activities carried out by different types of firms, it is also important to look at the way that large capital projects actually unfold. In a modular network, co-ordination should be achieved through the exchange of codified information, and arm's length market relationships (Sturgeon, 2002). It is important then to look in detail at the actual project management strategies implemented by firms when designing and building new capacity.

It is worth noting that these firms do maintain capabilities on complex and critical process steps, such as reaction modelling, catalysis and catalysts, and separation processes. As pointed out by the interviewees, chemical firms need to maintain these in order to be able to act as 'problem solvers of last resort'. Chemical firms that have outsourced and downsized without maintaining in house capabilities on critical process steps have become very poor clients for Specialised Engineering Firms (SEFs), as they cannot specify what they need, nor can they intervene when problems occur. Finally, and most importantly, the most effective project management strategies are characterised 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).

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novelty. Further, the data allow analysis (only in very aggregate terms, unfortunately) of up-front design performance with respect to different patterns of work organisation within specific projects.

[4] Unfortunately, the CIA survey asked about the extent of contractors' involvement by type of activity in 1990 only. The CIA officer in charge of the design and administration of the survey (contacted in 1999) stressed the difficulties that respondents have highlighted in providing 'average' figures for the 'average' project. So great is the number and type of projects chemical engineers are involved in at any point in time, that they find it extremely difficult to average out differences. For the same reasons it was impossible to replicate this question during the interviews.

Data provided by practitioners and interviewees demonstrate that projects where contractors have full responsibility from the very early stages of project definition (with almost no input from the owner) are those that exhibit the worst overall performance. Figure 2 reports some performance indicators relative to cost growth (over 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 produce outstanding results. As pointed out by many interviewees, due to the loss of experienced personnel, operators are finding it increasingly difficult to define the overall goals and technology requirements of their projects. The best performers are the 'integrated' projects, where contractors are brought on board early and the lead is taken by whomever retains the capabilities that are relevant to the project.

Rather than tight division of labour, good project performance requires increasing integration (within projects) between operators and contractors. What was dis-integrated (in terms of in-house detail design capabilities) has to be re-integrated by an open and integrated project management. 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}

3.3. Engineering design as problem solving

But why this increasing 'integration' at project level? The division (and modularisation) of engineering labour is limited by the by the nature of engineering design as a problem solving activity, rather than by the extent of the market *per se*, or the characteristics of the product. Interview data were used to decompose engineering design activities into two 'modes' of problem solving: analysis and synthesis. 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). Synthesis suggests the capability to envisage the decomposition of a complex problem into a tree of simpler problems amenable to being solved analytically in near-isolation. 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.

This practice of selecting out inferior alternatives by winnowing out the sub-problems they bring lies at the core of conceptual design activities. In chemical engineering, this phase is usually called process synthesis. Given its inherent complexity, process synthesis requires a thorough understanding of the business opportunities, the chemistry of processes, and the whole array of technological problems involved in the process scale-up.

In the words of one interviewee:

> Modularization is not an answer in and of itself. You still need to have the right team of people to decide what kind of process and product you are talking about, whether a modularised approach is the best one or not, how modules are to be

> linked with one another. Modularization can be a means to deliver the best possible way of doing things, but to understand this possible way you need an “integrated” understanding of your plant and process. They are useful in delivering flexibility and ease of construction, but they do not substitute a thorough understanding. You don’t need a detailed understanding of how a module works. All you need to know about is the range of operability of that module. How does it fit my needs? You may reduce your understanding of the mechanics of the module, but you still need a good deal of higher level understanding of the process (Interview, 1997)

Process synthesis activities are a tiny percentage of the total costs involved in a large capital project.[5] However, decisions taken at this stage have an enormous impact on overall project performance. Alternative process routes have to be evaluated on the basis of the sub-problems they generate. In a sense, ‘the appropriate description of the sub-problem contains the genesis of the solution’ (Marples, 1961: 65). The capability of predicting the unfolding of the sub-problem tree is the key capability required of process engineers involved in conceptual activities. As alternative solutions paths are decomposed, the sub-problems they generate must be analysed and evaluated in order to identify and discard inferior solutions. It is interesting to focus on the differences between synthesis and detailed engineering activities as put forward by the Chief Process Engineer of one of the companies:

> I have worked in the central process engineering unit of an operator and they are much less efficient than contractors. There is much less pressure. The amount of time you spend doing something else is much greater. Thus, the cost for productive hour is significantly higher. Unfortunately, what people who look at these higher costs forget, is that these engineers in operating companies spend a lot of time in selecting things that do not deserve to be pursued any further. Contractors are instead geared towards achieving a better-defined objective: get the plant built. Contractors are often not as good in dealing with all the uncertainties connected with the very early stage of the design process. Those who emphasise the "core business" argument tend to forget that one of the main functions of engineers in an operator is to get through this great mess of possibilities and find out the few sensible, practicable ways to go. And they are much more efficient in that than contractors are (Interview, 1998)

Conversely, the aim of designers in analysis mode is to check that all sub-problems within a given system can actually be solved in a consistent manner and all process stages deliver what is expected of them. 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. The exploration of specific sub-trees is a fundamental step at the conceptual design stage. This is why chemical firms that have reduced their direct involvement in engineering design activities, need to establish highly integrated and collaborative project environments: they need to access at an early stage the detailed engineering capabilities maintained by the SEFs.

{figure 3 about here}

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[5] Although difficult to assess, the rough and ready estimate that circulates in the industry indicates that process synthesis or, more broadly, conceptual design, costs amount to less than 10% of the total costs of a capital project. However, decisions taken at this stage directly determine 80% or more of the total costs.

3.4. Engineering design as a case of complex problem solving

Although distinct, these two problem-solving modes (i.e. analysis and synthesis) cannot be perfectly separated in cognitive terms. Technological-level and component-level factors determine the extent to which engineering labour can actually be divided. The nature of engineering design problem-solving (based upon the recursive exploration of hierarchically decomposed problems) requires engineers to explore major process alternatives in terms of the sub-problems into which they can be decomposed. 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 exploratory activities entail a sequence of synthesis/analysis problem-solving that limits the extent of division of engineering labour.

Near-decomposition (Simon, 1996) stems from the complexity of process engineering problems. Solutions can be found only by decomposing the problems into sub-problems, analysing the latter, and discarding search paths that present untreatable problems. It is this process of systematic generation of alternatives, decomposition, analysis and evaluation, that explains why engineering design is only nearly-decomposable. As engineers have to switch between synthesis and analysis mode a number of times during design, limits to the division of engineering labour emerge. It is just not possible to black-box all synthesis in conceptual design and analysis in detailed engineering, and separate them accordingly. Conceptual design involves a lot of detailed calculations (as flowsheets can be assessed only in terms of the sub-problems they generate), and detailed engineering also requires synthetic capabilities, as 'backward consistency' must always be checked for.[6]

Different design problems can lend themselves to different degrees of decomposition. Simple, well established products (e.g. trolleys, bicycles) may rely on sets of principles and architectures that allow for a level of decomposability that more complex products do not (e.g. chemical plants, aero-engines). The complexity of a problem is usually defined with reference to the degree or strength of coupling among sub-problems and the extent to which it is possible to decouple them (Marengo, 1998). In turn, the degree of coupling depends upon which specific pattern of decomposition is chosen by conceptual designers, i.e. how they frame the problem identifying the 'most relevant' interdependencies across elements.

This recursive process of analysis and synthesis limits the extent to which engineering labour can be modularised, and coordinated 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. Organisational 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, coordinated through markets and the exchange of codified information. Firms and corporate headquarters are not replaced by markets, but by the temporary hierarchy defined within a specific project. Hence, the emergence of less-than-modular, or loosely

[6] And also because some of the components are themselves systems of some complexity.

coupled, networks. In the next section, we explore the notion of authority on which systems integrators rely to coordinate loosely coupled networks.

4. AUTHORITY IN THE MODULAR AGE

The chemical engineering example provides insights into explaining the meaning and foundations of authority in the modular age. This section further explores the key finding in section 3: 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 explanation of the finding that integrators maintain capabilities at both the architectural level and the component level (e.g. Prencipe 1997; Davies, 1997). This section develops the discussion on problem solving in the case of chemical engineering activities, to discuss the functions and content that authoritative communications play in organising networks.

The key function of chemical firms involved in high-level design activities is to frame the problem by identifying the crucial technological and organisational interdependencies, and disregarding the rest. Given the combinatorial nature of process engineering, the essential synthesis-type problem is selecting out things that do not deserve to be pursued any further. This is consistent with the theoretical literature on complex problem solving. Engineers approach a complex problem by decomposing it into simpler ones that can be solved independently. However, as Simon (1996) pointed out, this process of decomposition cannot reach a situation whereby all sub-problems include all and only the elements that are independent of each other (i.e. a situation of perfect decomposability). Complex problems are only nearly decomposable. Moreover, the pattern of near-decomposition is not unique (Marengo, 1998; Marengo *et al.*, 2002). Problems can be framed in different ways, thus generating different patterns of decomposition. Engineering design activities aim to do precisely this: framing the problem in a specific way and thereby identifying the most relevant interdependencies, isolating them and exploring alternative decomposition patterns. Once the key interdependencies are identified, probed, and frozen, engineering labour can proceed organised in a much more specialised, and modular, manner. Specialists of distinct disciplines, problems and components, will work in isolation from other specialists.

The wide capabilities that integrators maintain in-house allow them to solve problems in a co-ordinated manner, i.e. co-ordinating specialist suppliers of components and knowledge through authoritative interventions. As stressed by Simon (1951) 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 authoritative. In turn, this willingness derives from the acceptance of 'zones of indifference' where recipients recognise that 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 maintain wider capabilities than any other single organisation involved in the design and engineering of a plant. SEFs appear, therefore, to be willing to accept the authority of operators whenever their own capabilities do not allow them to solve a specific problem.[7] 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 person or no single organisation 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 specialised 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.

The unfolding of engineering design activities helps us to understand what are the functions, and foundations, of authority in the modular age. In cognitive terms, the functions of authority can be summarised as follows. Authority is about deciding what decisions can be delegated to employees or project partners, and it is about deciding the limits to the discretion left to agents to whom decisions are delegated (Foss and Foss, 2002). In a sense, defining the span of delegation is exactly the objective of up front design activities, and synthesis as defined above. A complex problem needs to be decomposed into simpler sub-problems. In turn, the solution of each sub-problem is delegated to specialists (with the limitations already discussed).

This is a notion of authority that is somewhat different from that adopted in economic theory, traditionally based upon notions of control and monitoring of individual efforts. Foss and Foss (2002) provide an insightful discussion of different concepts of authority. In their terms, the concept of authority emerging from the fieldwork is quite close to what they call ‘Type II authority’, that is to say:

> … a decision right that an employer acquires, because he expects to obtain only ex post contracting the relevant information that will make possible the efficient delegation of discretion and the constraining of such discretion. (Foss and Foss, 2002, p. 5).

This definition, according to Foss and Foss, is less demanding in knowledge terms than the traditional definition of authority embodied in the approaches inspired by the work of Coase and Simon. The key point is that in the above definition the holder of authority is not supposed to select a specific course of action from within a set of discrete actions about which he or she has better knowledge than the ‘employee’ (the latter can only perform the course of action he or she is allocated). Rather, ‘in this definition, the holder of authority makes choices from a set of alternative possibilities of delegating’ (ibid.):

> [The holder of authority] does not necessarily have perfect information about 1) the members of this set, 2) how a given level of delegation maps into possible actions, and 3) the consequences of the relevant actions. In fact, Type II authority may be exercised precisely because the holder of authority wishes to stimulate a problem-solving process, the results of which he will be at least partially ignorant about. (ibid.)

[7] 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. However, the engineers interviewed in the fieldwork stressed the high-level ‘problem-solving’ role played by the operators’ engineering units.

In this context, the foundations of authority are to be found not only in the ownership of tangible assets, but in the capabilities that allow some firms (but not all) to frame [8] the problem, identify key interdependencies, and enact them. Following this framing stage, the division of labour can indeed be modular, but only once someone has made it so. And this ‘someone’ is a firm that maintains wide and broad S&T capabilities in order to be able to frame problems, and the division of labour around them, i.e. the systems integrators. These firms play a fundamental co-ordinating role within networks of specialised suppliers of both components and knowledge. Indeed

The literature on modularity is leading to a severe reconsideration of the nature and characteristics of the capabilities that underlie ‘authoritative communications’, and their scope. The above discussion on systems integration capabilities, and the differences between analysis and synthesis, highlighted that some firms need ‘to know more thank make’ in order to act as authoritative co-ordinators. However, they do not need to know everything about all the sub-problems identified at synthesis level. For examples, systems integrators do maintain in house capabilities about critical or complex components (e.g. reactors or separation systems), but not about all components. As pointed out by Foss and Foss (2002), the ‘holder of authority wishes to stimulate problem solving’, although within clearly defined boundaries. Such boundaries (across sub-problems, or components) are those identified at synthesis level. In other words, one can identify a hierarchy of nested problem solving cycles.

The level of abstraction decreases (Marples, 1961: 63) as engineers move down the hierarchy of problems and sub-problems, so does the number of degrees of freedom engineers can exploit in terms of searching for novel solutions. Conceptual design aims at defining one or more alternative patterns of problem decomposition (the problem tree) around the identified key interdependencies. Critical bifurcations along the tree will be explored early on to define the overall architecture of the problem, as major design decisions can only be compared with reference to the specific sub-problems they generate (hence the in-house capabilities on critical components). This process of recursive validation respects the hierarchical nature of engineering design (Constant, 2000). Paraphrasing Constant, if, for example, a problem arises with respect to a specific sub-module of mass and energy balance equations, say a specific process step appears to be producing more energy than it consumes, it is highly unlikely that any engineer will ever run down the street naked screaming ‘Eureka! The second law of thermodynamics is wrong!’ It is more likely that this engineer would roll up his/her sleeves and first double-check the calculations (were all process parameters inputted correctly?); then check the efficiency of the tools used to gather the original data (are all sensors working correctly?); explore the possibility that the software may not be being used within its normal working parameters (is this type of software designed to handle this type of problem?), and so on.

This hierarchical and recursive process of problem solving help explain how authority unfolds within networks of specialised problem solvers. In this context, ‘distributed

[8] Acha (2002) building on the concepts of sense making and salience, shows that framing capabilities are not only relevant to understanding why, and how, firms differ, but can actually be operationalised through interviews and quantitative analysis. She proposes the concept of ‘frame’ as the organisational construct through which the firm assesses its current position through sense making and explores its choice landscape (the environment, the competitors, the opportunities and the like) using the points of salience held by senior management. The frame is what enables senior managers to transforms data into information, and to select which data to analyse in the first place (Weick, 1995).

knowledge' held by specialised problem solvers does not necessarily lead to 'authority (as a centralized decision-making system) to fail in all its forms' (Grandori 2002: 257). Once the problem architecture is defined at the synthesis level, the systems integrator does not need to directly solve all problems, or observe others doing it, or being informed about all agents' decisions: respecting the boundaries of delegation set to each agent will suffice.

5. DISCUSSION AND CONCLUSIONS

The distinction between knowledge and product-level dynamics has important implications for innovation management and organisational sciences. This paper has argued that modularity at the level of the artefacts does not necessarily lead to modularity at level of the organisation. The emergence of modular networks is limited by the very nature of the social cognitive processes that underpin firms' problem solving activities (e.g. the links between analysis and synthesis). Linking authority to capabilities, as opposed to ownership, offers a way to understand how global networks of firms are organised by firms that know more than they actually do in house. This link extends Penrose's original definition of firms as a 'bundle of resources' bound together in an administrative framework, the boundaries of which are determined by the 'area of administrative co-ordination' and 'authoritative communication'" (Penrose, 1959, XI). In fact, authoritative communication can extend beyond the area of administrative co-ordination as defined by the direct ownership of tangible and intangible assets. First, some firms maintain wide (and even widening) scientific and technological capabilities that enable them to co-ordinate loosely coupled networks of specialised suppliers. Second, even in the presence of globalisation of manufacturing activities and increasing outsourcing of activities previously performed in house, project-based activities provide a temporary administrative framework within which some form of hierarchical co-ordination replaces the market. While problem solving *capabilities* provide the foundations for understanding authority in the modular age, *projects* appear as the organisational locus within which authoritative communications unfold.

This last point is worthy of more attention, and a little of speculation. Firms in a variety of sectors operate on a project basis. A project is basically a contract, or rather a bundle of contracts, that specify the duties, responsibilities and rewards of the firms involved in, for example, designing and building a chemical plant. To use again the 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 closure' for all the communities involved in the project, identifies the key technological and organisational interdependencies, sets a timetable, and allocates responsibilities. It is the result of the negotiation between the various communities that coexist within and between firms at all times. At the same time, the project is a temporary endeavour. While providing a common identity to all the specialised communities involved in the project, this identity will disappear once the project is over. This idea of a temporary identity clearly builds upon the notion of routines as 'truces' (Nelson and Winter, 1982) and that of 'quasi resolutions of conflict' (Cyert and March, 1963).

The growing literature on project-based firms (PBFs) identifies these firms as being characterised by the prevalence of project activities (as opposed to, for example, functions); their involvement in the design and production of customised products and services; and their involvement in wide coalitions of companies along the value chain (Gann and Salter, 1998: 450). In a sense, projects operate as ‘gates’ between the firm and the external environment. The concept of a PBF is similar to that of ‘adhocacy’ proposed by Mintzberg (1989). However, the PBF literature highlights the fact that projects are becoming an increasingly diffused organisational strategy in a widening range of sectors, from traditional manufacturing to innovative, knowledge-intensive service industries. Projects offer the promise of a rather effective tool through which firms can integrate the capabilities developed by the distinct communities of specialists that interact within, and across, them. In a fast changing environment, it is important that such integration does not lead to a permanent reduction in diversity - hence the importance of the ‘temporary’ dimension of project based activities. In a competitive environment, it is also important to be able to bring specialised 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 specific design package.

Research on the dynamics of project-based organisations is opening promising avenues along which to analyse and understand the relationship between cognitive processes and new organisational forms without black boxing them into the hollow concept of ‘hybrid organisational forms’.

Table 1. Driving forces affecting the outsourcing of engineering design.

Enablers (knowledge-related factors)	Pushers (incentives)
• Technological maturity	• Advantages of specialisation at the detailed engineering level
• Accumulated technological knowledge of component behaviour	• Pressure from developing countries to use local engineering centres
• Increasing use of ever more powerful computational capacity (and consequent standardisation of design processes)	• Low frequency of new construction in OECD countries
	• Increasing engineering costs

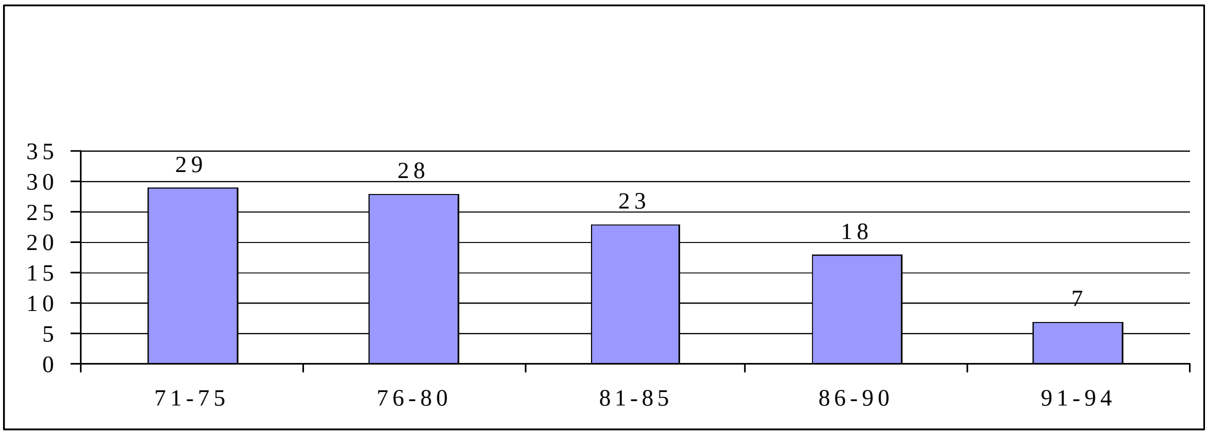
Source: adapted from Brusoni and Prencipe (2001).

Table 2. Share of outsourced project activities in 1990.

	% of total project costs	contracted out
design		40
engineering	16	60
project management		40
process plant on site fabrications	31	75
mechanical and electrical installation	32	85
civils and buildings	21	90
	100	

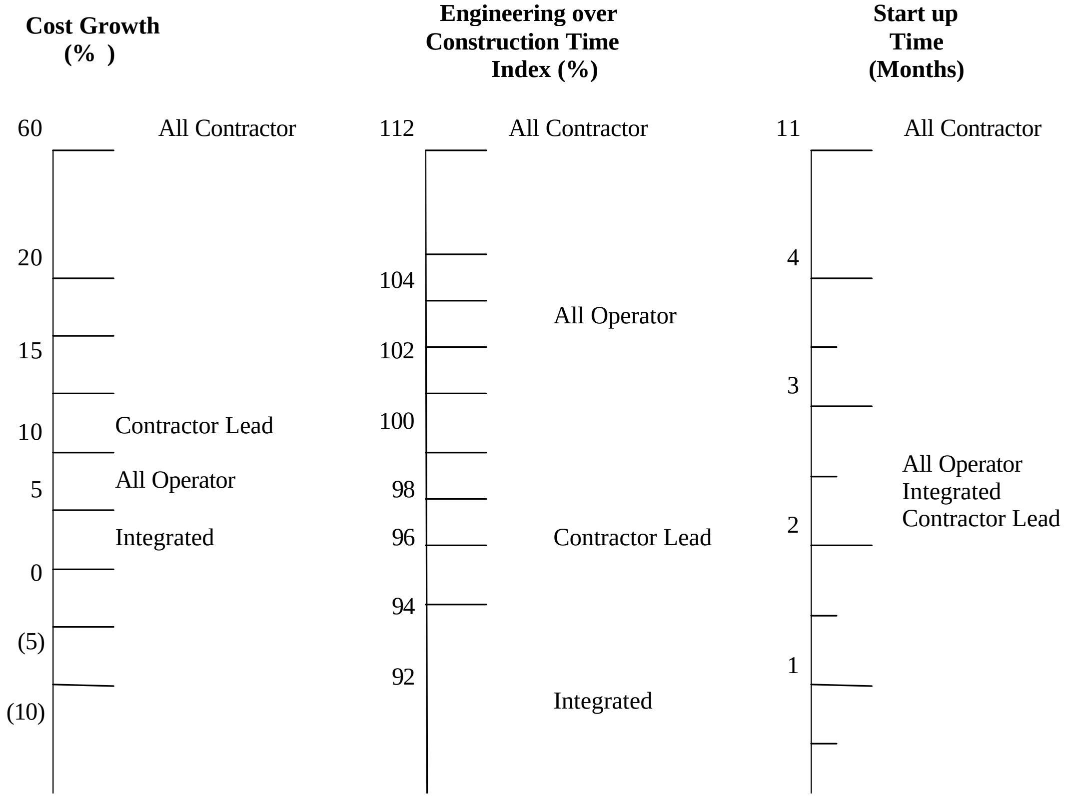
Source: CIA annual survey, 1990.

Figure 1.
Share of detailed engineering activities carried out by owners



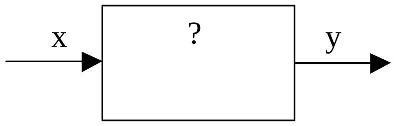
Source: adapted from IPA, inc.

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 world-wide, between 1985 and 1997. Data are normalised 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, optimisation, control

Source: adapted from Brusoni (2001)

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