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STRATEGIC PERSPECTIVES ON MODULARITY

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Abstract

In this paper we argue that the debate on modularity has come to a point where a consensus is slowly emerging. However, we also contend that this consensus is clearly technology driven. In particular, no room is left for firm strategies. Typically, technology is considered as an exogenous variable to which firms have no choices but to adapt.

Taking a slightly different perspective, our main objective is to offer a conceptual framework enabling to shed light on the role of corporate strategies in the process of modularization. From interviews with academic design engineers, we show that firms often consider product architecture as a critical variable to fit their strategic requirements. Based on design sciences, we build an original approach to product modularity. This approach, which leaves an important space for firms' strategic choices, proves also to seize a large part of the industrial reality of modularity. Our framework, which is a first step towards the consideration of strategies within the framework of modularity, gives an account for the diversity of industrial logics related to product modularization.

Keywords: Product modularity, corporate strategy, technological determinism

JEL : L21, L22

Introduction

In 1962, Herbert Simon introduced “Near Decomposability” as a specific configuration of a complex system, allowing to guide its structural dynamics towards an effective equilibrium regarded its environment. In 1964, Alexander thought modularity as a design rule making it possible to overcome the cognitive limits of individuals. Not surprisingly, these concepts have been first used in design sciences (mechanics, electronics, data processing...). Spurred on by the work of Parnas (1972), Modularity principles were notably applied to software design and to the IBM OS/360 operating system (Brooks, 1975) in the Seventies. Nowadays, many products are, or are likely to be modularized.

Since the pioneering contribution of Starr (1965), the economic and organizational implications of modularity have received great attention. These works take place within a debate concerning the links between technologies and organizations. The common assumption refers to an isomorphism between product architecture and organizational architecture. The more the product is integrated, the more the firm in charge of its design and manufacturing is integrated. Reciprocally, a modular product design leads an organization towards more modularity. As proposed by Sturgeon (2001), a modular organization is characterized by the presence of an “architect” firm and independent suppliers, tied up by market-based relationships, as well as codified knowledge exchange.

At the heart of these discussions lies the notion of product design (i.e. its description or its architecture). The concept of product architecture was suggested by Ulrich (1995). It corresponds to the product’s fundamental structuring concept. His definition exhibits a double dimension, including both the nature of component interfaces and the mapping from functional elements to physical components.

However, the discussions among economists we mentioned above are primarily based on interface standardization. For instance, works of Momme and al. (2000) or Hsuan (1998) came to be built on the mere distinction between strategic and non strategic components (or standard and specific systems). Further, Genthon (2004), while studying the computer industry, reaches the same conclusions as the proponents of modularity without using this concept. So, what’s new with modularity?

This focus on interactions between components leads indeed to a “technology driven” analysis of product and organizational design. Indeed, the density of interactions is, by its very nature, subject to physical and technological constraints. Moreover, industry-wide interface standardization processes are almost always out of control of any single firm. Hence, organizations are completely subject to technological constraints. Finally, these works do not manage to seize the strategic importance of product architecture, which could be the real novelty in modularity.

We believe that much of what one can say about modularity and its economic consequences depends on the definition one chooses *a priori*. This point, missed by most economists, is very important to us. The definition used by economists is the one mentioned above. However, the functional nature of product decomposition, albeit useful in many cases, is a relatively narrow base for a definition of product modularity. Indeed, it is only an alternative among others. Since the way the product is decomposed is *a priori* given, economists have paid very little attention to this process. Interestingly enough, we were told that this decomposition is typically a strategic decision.

We wish to suggest a broader approach to product modularity allowing to centre the economic analysis on firms' search for competitive advantage. This approach rests on the non-characterisation of product decomposition *a priori*. In other words, we do not presuppose of a functional breakdown. The technological determinism of previously quoted works is thus considerably attenuated. In addition to the central place it gives to the firm, this definition proves to be consistent with industrial practice. Indeed, the comparison between Ulrich's concepts and "industrial definitions" indicates a gap between theory and practice. In particular, the reality of modularity seems to be very heterogeneous. Our definition makes it possible to encompass this diversity.

Part I. Modularity and industrial organization

For most economists, modularity is a theoretical concept enabling to read industrial organization dynamics with respect to product innovation. This way of looking at modularity is underlying the debate concerning the links between technologies and organizations (for example in Langlois, 2004 or Langlois and Savage, 2001). Typically, these works begin by roughly describing product architecture and then speculate about organizational consequences. More precisely, this debate brings into conflict the proponents of a "modular organization" and those of an organization coordinated by a "system integrator". A first definition of a modular organization underlines the presence of an "architect firm" whose role is to specify general design rules. The standardization of interfaces generates an informational structure allowing what is labeled as "embedded coordination" (Sanchez and Mahoney, 1996). The specification of industrial standards would ensure an effective coordination between loosely coupled units. This would thus cancel the need for managerial coordination in interfirm relationships. Therefore, each unit could work independently on a module, while having confidence that the product works as a coherent entity. As an ultimate consequence, it would lead to intensify the division of labor (Frigant, 2004). More precisely, companies would be able to assign modules' detailed design and manufacturing to specialized suppliers in order to benefit from the well-known advantages of specialization. Langlois and Robertson (1992) find evidence of such decentralized networks in the computer industry and in the development of stereo systems.

On the whole, as modularity is a product structuring concept, that notion is also an industry structuring concept. As a matter of fact, the way a firm articulates its resources deeply influences industrial architectures. Resources available for a company include its internal resources, "relational resources" controlled by other firms, and market resources (Sanchez, 1995). The variety of resources available, as well as their accessibility, increases with the capacity of firms to use modular product architecture to coordinate an extended network of productive resources (Sanchez, op.cit). Within a modular framework, all the resources involved in the production process can be mobilized in a parallel and autonomous fashion. When component interfaces are perfectly specified and standardized across the industry, a modular network allows many entry points for external suppliers (Langlois and Robertson, op.cit). The lowering of technical barriers to entry leads to an intensification of the competition on modules. This enhances incentives among suppliers and makes it possible for the assembler to choose among a great number of modules. In addition, the multiplication of differentiated modular components available allows firms to modify the final configuration of their products according to market needs. Wooren and al. (2002) find evidence of such strategic flexibility in the UK home appliance industry. Moreover, this approach challenges the sequential organization of complementary activities. Indeed, in this context, the work of each unit does not depend any more on that of others. This is due to the fact that each firm knows *ex ante* the specifications, contained in the output of others, which will be useful for its own role in the production process. It results that the process of resources mobilization can become concurrent and more flexible.

Meanwhile, competitive pressure considerably erodes suppliers' position. Thus, another feature of modular organizations is the presence of large specialized suppliers serving many markets. The modular supplier model corresponds to a large firm having significant competences in detailed design, and large enough to allow the whole supply chain to benefit from external economies of scale. This model is exemplified by electronic manufacturing services. Many end products, such as mobile phones, computers, printers... are made up of electronic modules. These modules are single or assembled printed circuit boards and electronic chips. For printed circuit boards, Sturgeon notices the rise of contract manufacturing services. Firms such as Solecton, Celestica or Flextronics are large specialized suppliers serving many customers in different industries (Sturgeon, op.cit).

In Chip design and manufacturing, a process of vertical disintegration also occurs. Indeed, design is often done independently from production in the so called fabless design firms and chip foundries. This has been labeled as the Silicon Valley model or modular clusters (Baldwin and Clark, 1997, 2000) and this is related to the development of markets for technology (Arora and al, 2001). Here, the main novelty lies in the decoupling of design from manufacturing (Sturgeon, op.cit).

However competing business models do exist. For example, firms like Phillips or Toshiba are still vertically integrated. Moreover, it is still common for semiconductors to be designed and manufactured by integrated device manufacturers such as Motorola or Intel. In addition, more specific chips (ASICs) are often kept in house by lead firms like Sun or Cisco (Sturgeon, 2003).

In these cases, product modularization does not seem to be the discriminating element. For instance, authors stress the modular aspect of productive organisation but pay very little attention to the corresponding product modularization. According to them, these trends were primarily made possible by the availability of standards, process standardization, technological convergence and the development of IT. For example, according to Macher (2000), process standardization regarding CMOS technology played a major role in this course of disintegration

At a higher level of modularization, the Computer industry has been the locus of another process of vertical disintegration (Langlois and Robertson, op.cit). Considering the computer as a network of complementary products, the functional specialization is clear. Many firms such as Logitech, Lexmark or Epson are specialized on these peripheral products. Software designers are also part of this functional decomposition. Since this level of modularization has to do with our day-to-day final use (final functions vs technical functions), the links between technological and organizational trajectories may be more understandable and obvious. For instance, the modem makes up for 90% of the function “external communication” (Fixson and Sako, 2001). This stand-alone subassembly has standardized USB interfaces and functions seamlessly with any model of computer. Further, it can be bought from many producers.

In contrast, those in favour of system integration claim that modularity is limited because of the cognitive limits of firms. The growing number of specialized knowledge fields embodied in a single product challenges firms to coordinate many specialized and local bodies of knowledge. Consequently, market-based relationships would not be sufficient to ensure effective coordination. Given this, a firm would have to play the role of network coordinator. The proponents of this approach rest on empirical observations, and in particular on the fact that there is a gap between knowledge firms need and knowledge they have indeed: "Firms know more than they do" (Brusoni and al., 2001 and Brusoni and Prencipe, 2001). More precisely, firms keep knowledge about activities they have externalized in order to ensure the interface with their core competences.

Brusoni and al. (op.cit) contend that the design process cannot be perfectly decomposed because design rules evolve over time. Moreover, products such as cars or planes are so complex that they include modules that are themselves composed of sub-modules... In this setting, the definition of design rules may require a very precise modular knowledge. Brusoni and al. explain also that when a module includes technologies that have different evolution paces, the organization requires the presence of a "system integrator" that has the ability to understand these technological gaps (Frigant, op.cit). In particular, as a technology emerges, interactions might not be well understood by producers and therefore difficult to predict. Consequently, interfaces cannot be frozen *ex ante* and interactions between suppliers and system designer are deep because of the need to adjust component interfaces to the evolving design rules.

The division of labour is thus limited by the non divisibility of knowledge. These works do not deny the process of vertical disintegration, they only explain why it is limited. Therefore, the discrepancy lies in the role of the lead firm and particularly its role as far as coordination is concerned.

At first glance, one could say that the essence of the debate comes from the fact that these two theories are not interested in the same industry. Those concerned with electronics observe a high level of standardization, specialized design firms, modules bought off the shelf, whereas those interested in the automotive industry note a deep cooperation between suppliers and customers, co-design practices...

We are then left with two different organizational realities. And, not surprisingly, these two theories come up against the same difficulty: Generalization (Ernst, 2004). The implicit assumption underlying these discussions is that the most efficient organizational model will tend to dominate.

The advocates of system integration mobilize a resource-based view as well as an evolutionary approach to explain the superiority of their theory. More precisely, they draw on authors like Penrose or Richardson to justify the coordination between complementary activities. By contrast, Baldwin and Clark rest on Transactions Cost Economics and Agency Theory to explain the efficiency of market-based relationships in a modular environment and, more precisely, the opportunity for decoupled organizations to exhibit flexible specialization (Piore et Sabel, 1984), Dynamic capabilities (Teece and Pisano, 1994), or strategic flexibility (Sanchez, op.cit). The main difference therefore lies in the view of the firm. The modular approach consider the firm as a “conventional” information processor with a subsequent emphasis put on contracts (as in Fujimoto, 2002), whereas in the system integration perspective the firm is considered as a knowledge processor which brings about problems of cognitive distance, absorptive capacity... (Cohen and Levinthal, 1990).

None of these predictions is however corroborated by empirical studies. Instead, it seems that there is coexistence of these organizational models. Aoki (2002) explores three types of modular organizations. The “hierarchical decomposition”, in which the lead firm acts as a system designer, looks like Sturgeon’s description of electronic manufacturing services. The “information assimilation”, where module suppliers are involved in system definition, resembles the case of automotive industry. The model of “evolutionary connection” corresponds to the “Silicon valley model” where multiple agents are engaged in the design of the same module.

These observations would tend to mean that each of these theories is valid for the industry it was initially interested in. In other words, these two approaches would not be opposed but rather very complementary.

Thus, Brusoni, Prencipe and Pavitt (op.cit) have bridged these theories within a single typology.

		Systemic interdependencies	
		Predictable	Unpredictable
Rate of change of component technology	Low	*Modular Network*	*System Integration*
	High	*System integration*	*Thightly coupled Network*

The proponents of modularity would then discuss only a specific case of this table. The one concerning products whose characteristics are perfectly defined, well understood and mastered by designers

As we mentioned in the introduction : The more the product is integrated, the more the firm in charge of its design and manufacturing is integrated. Reciprocally, a modular product design leads an organization towards more modularity. This view is confirmed by the work of Novak and Eppinger (2001) for the automotive industry, who finds that the more complex the system is, the more it is likely to be produced in house.

A dynamic way of bridging these approaches has been found by Chesbrough (2003). Here, the stage of the technological cycle is the discriminating element. As a technology emerges, interactions are not well understood by engineers. Interface management then requires integration competences in order to ensure that the product works as a coherent entity. When the industry stabilizes around a dominant design, interfaces become more standardized, and less integrated organizations are a more viable way of doing business. When the technology reaches its theoretical limits, engineers look for fundamentally different design approaches. A new architecture will enter a stage of fermentation to end up with the selection of a new dominant design. His claims are supported by a study of the hard disc drive industry. Besides, this is in line with Afuah's (2001) argument of the dynamic boundaries of the firm.

Others have carried out a similar analysis in terms of knowledge maturity (Foss and al., 2000). However, these analyses are mainly technology driven and no room is left for corporate strategies.

Thus, the frame where these works have proved to be the more relevant is the study of innovation and technical change. In particular the distinction between architectural and modular innovation (Henderson and Clark, 1990) has brought considerable insights in our understanding of organizational changes. Modular innovations can be efficiently managed by decoupled organizations. In particular, the rate of innovation can be speeded up to the extent that it involves the trying out of many alternate approaches simultaneously, leading to a rapid trial and error learning (Langlois and Robertson, op.cit). However a possibility of "modularity trap" (Chesbrough and Kusunoki, 2001 ; Chesbrough and Teece, 1996) arises in case of architectural innovation. For example, Galvin and Morkel (2001) claim that independence of component suppliers in the world bicycle industry prevent them from introducing architectural innovations. Similarly, in the semiconductor industry, Macher (op.cit) found that integrated device manufacturers achieve performance advantage over foundries for process innovations requiring great coordination between design and manufacturing. These questions highlight the problematic distinction between architectural and modular knowledge (Arora and Gambardella, op.cit and Sanchez, 2000), which come to be the very heart of the discussion.

Another meaningful insight of these works is that they take into account changes in product architecture. However these changes arise mainly due to external factors. We thus wish to set a framework underlying firms' role in the modularization process. Our intuition is that corporate strategy may have strong implications in terms of organizational outcome (Chandler, 1990 ; Lawrence and Lorsh 1967 ; Thompson, 1967...).

Part II. Product modularity: an industry-oriented definition

A lot of definitions of product modularity have been given. Roughly, we can distinguish two broad categories:

- Interdisciplinary definitions from Ulrich and Eppinger (2004) and Baldwin and Clark (op.cit).
- Definitions in design sciences often very specific to their application field. However, a synthetic work has been recently made by Gershenson et al. (2003, 2004).

Interdisciplinary definitions

Seminal works of Ulrich (op.cit) and Baldwin and Clark (op.cit) are essential for economists insofar as they allow the characterization of products according to their degree of modularity.

Like any complex systems, products tend to be hierarchically shaped (Simon, op.cit). Indeed, their functional and physical structures form hierarchies. More precisely, they form nested hierarchies. Product structures and functions are composed of subsystems, themselves divided into subsystems... Thus, product architecture is defined as the way in which functional elements are connected to physical components (Ulrich, op.cit).

The allocation between functions and components is said to be modular when it exhibits a one to one mapping between functional and structural elements. The underlying idea points out that a complex system can be more simply addressed when broken up into several subsystems. The perfect mapping between functions and structural elements makes it possible for the system to present natural breakable joints, authorizing a “clean” decomposition (i.e. which “does not break” any interaction between components and functions). The different subparts of the system can then be insulated easily so that the product forms a near decomposable system (Simon, op.cit).

If a single component implements several functions (function sharing), or conversely if a single function is fulfilled by several components, the product architecture migrates towards more integrity. It is difficult to break such a system into modules without loss of functionality because some links between physical and functional elements can “be broken” during the decomposition.

Interfaces define the relational characteristics between components. They embody some rules which specify the way in which components interact. Interfaces are defined by the level of independence they generate between modules and by their level of standardization. In this respect, product architecture is modular when interfaces are perfectly decoupled (a change made to one component does not affect any other component), and perfectly standardized (they accept the connection of a broad range of components) (Ulrich, op.cit). To meet this second condition, interfaces have to adhere to a standard input-output protocol. The parameters of connection to the system (input), as well as the functions to be filled within the system (output), have to be fully specified, codified and shared.

Defined in such a way, interfaces make it possible for a system to exhibit weak interactions between its subsystems and strong interactions within them, which is a feature of modular structures highlighted by many authors. These systems are assembled in a “loose” way. They can be reconfigured easily and in a flexible fashion, without loss of functionality. Conversely, subsystems of integrated products exhibit complex interactions. Each component is arranged in a specific way, aiming at achieving a high level of performance. The combination of components achieves a synergy through specificity that those acquire within a particular configuration (Schilling, 2000). The impossibility to move the components without loss of functionality is captured by the expression “tightly coupled systems”.

According to these two characteristics (interfaces and function-component mapping), products are located on a continuum representing different levels of modularity.

Baldwin and Clark’s focus on visible design rules underlines the importance of independence between modules. The product is seen as a bundle of design information. The modular approach rests on a partition of this information. Each module is characterized by specific information and by rules which define its place, its role and its interaction modalities. The latter are labeled as “visible design rules”[1]. It follows that it is possible to break up the informational bundle embodied in the product, according to these two sets of information. “Hidden information”[2] or “encapsulated information” (Cremer, 1990), corresponding to module-specific parameters, does not need to be transmitted to all the units taking part to the design and/or the production process. “Visible information” represents the decisions which affect the whole architecture and which need to be shared among all participants.

The vision of Baldwin and Clark may give a more explicit account for the organizational stakes related to a modular product design. Indeed, the confinement of module-specific information imply that once the "visible design rules" are defined and frozen, each unit can work in a perfectly autonomous and independent way, with the only concern of specifying interfaces compatible with the “visible design rules”.

By contrast to Ulrich’s definition, Baldwin and Clark do not adopt a functional perspective because they consider it as a difficult and subjective process.

Limits of these definitions and insights from design sciences

The common essence of these definitions lies in the presence of strong interactions within modules and relatively weak interactions between modules. Whereas the simplest definitions consider a modular product architecture as a one-dimensional concept regarded the nature of interfaces[3], these definitions indicate that product architecture is a multidimensional concept. In particular, interfaces and standards on the one hand, and modules’ organization on the other hand, are two sets of characteristics in themselves. However, these definitions are only theoretical references and products are never perfectly modular. It appears to be more relevant to consider products as located on a continuum representing different levels of modularity. However, our contribution is not limited to the suggestion of considering several levels of modularity. What we offer is a broader approach to product modularity. For example, the definition of Ulrich rests primarily on a functional decomposition. Meanwhile, as put it by

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[1] More precisely, visible design rules fall into three categories (Baldwin and Clark, op.cit):- An architecture which specifies what modules will be part of the system and what their functions will be.- Interfaces that describe how the modules will interact. - Standards for testing module’s conformity to the design rules.

[2] This concept was introduced by Parnas (op.cit). He had in mind that the programmer is most effective if shielded from, rather than exposed to the details of construction of system parts other than his own.

[3] Interfaces are discussed along their open/proprietary nature and their standardized/specific dimension, as in Garud and Kumaraswamy, 1993.

Baldwin and Clark, the functional hierarchy is very subjective and depends on the level of abstraction adopted. For instance, consider a hair dryer (Fixson, 2003):

"Its main function is to dry hair. If to dry hair were selected as a function, the result would be the allocation of this function to all components, for all components of the hair dryer would exist in the first place if it were not contributing to the product functionality. On the other hand, if the function is chosen on a very low, detailed level : "Hold part A in position X relative to part B with force f", then exactly one and only one component delivers these functions...In contrast if one begins to define functions like "to generate air flow, heat air flow, control heat, control air flow, supply energy"..., then it becomes meaningful to investigate how functions are mapped to components".

One can argue that considering functions with respect to final use is relevant, but reality demonstrates that functions related to the final use are not always easily identifiable. For example, Muffatto and Roveda (2002) account for the difficulty in distinguishing between "real" functions and "subfunctions" which deliver technical functionalities intended to ensure the working of other functions. Moreover functions related to esthetism are often truly global and cannot be contained in a single module. In the definition suggested by Baldwin and Clark, the decomposition is also viewed from a single angle (i.e interactions between modules).
On the whole, the main failure of these definitions is that they consider only one way of breaking up the product.

Works in design sciences are inspired by seminal writings of Suh (1990), whose three design axioms are recalling modularity principles. Besides Ulrich's definition, many other works exist. However, one can notice a kind of convergence towards Ulrich and Eppinger's concepts. Indeed, a functional perspective is often adopted because designers generally take a prospect consisting in transforming customer's requirements into functionalities (Pahl and Beitz, 1984).
Meanwhile, we were told that the works of Ulrich have to be taken very carefully. According to Blanco, a functional decomposition is not always possible (even desirable). Other logics of decomposition are possible, such as the grouping of components according to their life cycle. This approach is confirmed by the work of Ericxon (1996) who identifies several drivers for product decomposition. Gershenson and al. (op.cit) show that a module exhibits both an element of "independence" (few interactions with other modules, as we saw) and an element

of “coherence”. In the definition of Ulrich this element of coherence is the function (all the components within a module fulfill the same function), but many others are possible.

These elements being grouped, they must be independent on other modules. It is then relevant to investigate interfaces’ characteristics whose “role” is precisely to limit or to standardize physical interactions between modules. Finally, designing a module is constraining insofar as the groupings need to be both coherent and independent. It is also interesting to note that whatever the logic being adopted, there might be a trade off between the coherence of product decomposition and the level of independence between modules. Consequently one could not maintain that a product is modular without having specified the nature of decomposition under consideration. And it is all the more significant when the degree of modularity of two products is compared. A little as for fractions, one needs a common denominator which authorizes the comparison : This common denominator is the coherence of the module. Saying that a car is less modular than a computer would not be very relevant. If a functional breakdown is considered, then this is true (Fixson and Sako, op.cit). However, in the car industry, the modules are not designed according to a functional logic but according to their physical localization in the end product (SESSI, 2003). Then, observing the final assembly lines at car manufacturer plants leads us to think that this way of decomposing the car, together with investments in machines, involves a relative independence of modules during the final assembly. In addition, two other points are confirmed by design sciences: First, modularity is a relative property (i.e products are more or less modular). Second, the level of modularity depends on the level of abstraction adopted to analyse the architecture.

An industry oriented definition

Building on these two sets of works, we suggest the following definition of product modularity:

Coherent product decomposition into subsets, made up from the integration of lower order elements, whose interactions are limited. These subsystems are called modules and interact with each other via interfaces.

This definition can be divided into two axioms. We shall specify them:

The coherence axiom

We were told that the logic of decomposition is a decision leaving a room for strategic choices. This is related to methods of DFX, where X may correspond to one of dozens of criteria (the most common of these methodologies being design for manufacturing and design for assembly). The functional decomposition is therefore only one possibility among others. Besides functional decomposition, following Marshall and Leaney (1998, 2002), we can consider the following logics to product breakdown:

- Interactions: To gather within a module, the elements whose interactions are numerous or fundamental (approach of Baldwin and Clark).
- The physical location of components: To integrate in a module the elements which require a physical proximity as it is the case for the car.
- Supplier competences: A supplier can have a specific expertise in such a way that it is profitable to group the elements coming under his responsibility in a module.
- Core competences: To gather the elements related to the core competences of the company so as to be able to externalize the other parts.
- Manufacturing process: To gather the components which require the same manufacturing process.
- Platform logic: One can also gather all the elements that can be reused on other models or other products (see also, Ulrich and Robertson, 1998).
- "Natural modules": Groups of elements which are complementary and which benefit little from being separated, for reasons of performance for example.
- Localization of change: When probable evolutions are anticipated, the elements likely to change can be grouped in a module so as to limit the systemic effects.
- "Configurability": The elements are grouped so that the company can combine the modules in different manner to offer variety (home furniture sold in kit or modular buildings).
- Element of differentiation: To group the elements which together represent an element of differentiation for consumers.
- Recycling process: To gather components in order to ease recycling processes.

The independence axiom

This axiom has to do with interfaces and interactions between modules. Ulrich determines two features to characterize an interface: its level of standardization and its degree of coupling. Its degree of coupling represents the level of independence between the connected modules and its level of standardization refers to the number of alternative components available. The degree of coupling depends on the nature of both interfaces and interactions (an interaction is a flow going from a module to another, whereas an interface is the locus, the physical support of this interaction). Interactions can be related to a material transfer, energy transfer, electronic signals or information exchange... (Eppinger and Pimmler, 1994). Interfaces can be materialized by bolt-nut or snap-fit connections, points of welding, wires, electronic controlling devices ... (each of them being more ore less constraining). The level of coupling also depends on the interface localization in the end product (its ease to be reached by operators) (Fixson and Sako, op.cit).

The level of standardization is given by the number of alternative modules available. It is what Ulrich has called "component swapping". If one considers the module, the relation is reversed: It is the number of alternative products available for a given module which represents the level of standardization. It is, in Ulrich's terms, a case of "component sharing modularity". Of course, these two types of modularity can correspond to the same thing depending on the element considered as the system and the element considered as the module. For example when the same mouse is used on two different computers, it is "component sharing", whereas if one changes the mouse on a computer, then the term "component swapping" is used (Fixson, op.cit).

Finally, it is important to understand that most end product architectures are mixed. Firstly, interfaces are different according to the module under consideration (some are standardized, other not...). For example in the automotive industry, except simple subassemblies such as the wheels, few parts are standardized. Further, Warburton and Sako (1999) report that the composition of the cockpit module varies from manufacturer to manufacturer.

Figure 1

Secondly, various logics of decomposition can coexist inside the same product. This variety can involve trade offs. For example, Kinutani (1997) notes that modularity at Mazda was spurred on by manufacturing engineers in order to ease final assembly, and that it brings them into conflict with product engineers who have different goals.

Finally, one can say that products are composed of core modules (platforms) shared across products and more flexible modules that allow for differentiation.

Besides, this approach is very close to the one used in the "object oriented design methodology" where modularity is defined as a property of a system which was broken up into a few coherent and connected modules (Booch, 1991). The element of coherence of the module lies here in what is called “the class”.

Measures and methodologies

Let us now turn to the implications of such a definition on measures and methodologies of modular product design. Concerning the independence axiom, we do not notice any change compared to existing methods. Modularity can be represented by a matrix where components are listed in rows and columns in order to spot interactions. This is what has been labeled as the *design structure matrix* (Baldwin et Clark (op.cit), Newcomb et al, (1996)). Analysing these interactions and interfaces that support them is necessary. For example, tools suggested by Fixson or Eppinger can be used.

We have now to deal with the coherence axiom. In a functional perspective, many design tools have been developed. Meanwhile these tools are not very relevant in our perspective. Gershenson et al. (op.cit) suggest to use a second matrix to display the coherence of the module. For example they use both a component-component matrix and a component-component life cycle matrix. Erixon (op.cit) first identifies the functional architecture, then tries to find technical solutions to these functional requirements, and finally elaborates a matrix where these technical solutions are confronted to various elements of coherence (*Identification Module Matrix*). These technical solutions become effective modules if the parts that constitute them are sufficiently homogeneous with respect to other coherence criteria.

“Object oriented design methodology” and “holonic product design” (for example, Marshall and Leaney, op.cit) are promising avenues to develop tools and methodologies for modular products.

Consistency with industrial practice

The definition given by many industrial managers is based on the concept of module. However, this definition varies from one industry to another, if not from firm to firm (Gershenson and al. op.cit). From our definition of product modularity, it comes that the definition of a module is contextual. It depends mainly on the nature of product decomposition and, more generally, on technological feasibilities and corporate goals.

In software design, modularity usually refers to "tools for the user to build large programs out of pieces" (Chen 1987 – quoted in Gershenson and al., op.cit). The definition of a software module is often given in terms of functions. One such definition is that, for a given function, there is no access to, informational flow to, or inter-activity between modules (George and Leathrum, 1985 – quoted in Gershenson and al., op.cit). The reuse of existing codes in also often stressed in software design, as well as the opportunity to work in parallel:

« With the Linux kernel it became clear very quickly that we want to have a system [that] is as modular as possible. The [FS/OSS] development model really requires this, because otherwise you can't easily have people working in parallel. It's too painful when you have people working on the same part of the kernel and they clash ». Linus Torvalds creator and principal software architect of Linux - quoted in Garzarelli and galoppini, 1998.

In programming languages, the procedures, subprograms, or packages represent the modules. The term module here refers to a 'manageable portion' of the code (Spencer, 1998 – quoted in Gershenhon and al. op.cit).

In computer industry, modularity represents the building of complex products or processes from smaller subsystems that can be designed independently and yet function together as a whole' (Baldwin and Clark, op.cit).

Construction modularity in the home building area is said to be an important part of the economic future of the construction industry. It can be defined as using sets of units designed to be arranged or joined in a variety of ways (Civil Engineering Research Foundation, 1996). For submarines, construction modularity has been defined as design with subsystems 'that can be assembled and tested prior to integration . . . to reduce the time and cost of manufacturing' (Carey 1997 – quoted in Gershenhon and al. op.cit).

In the home furniture industry, the modularity is defined, at SauderWoodworking, as a concept making it possible for the consumer to design its furniture himself (design it yourself). In electronics, modules are interchangeable blocks, whose assembly is done without welding (www.granddictionnaire.com).

For space systems, modularity is often seen in a functional perspective. For instance, US space systems for military applications are on the road to modularity. In this case, modularity refers to the use of small, lightweight modular satellites placed into orbit by light lift, then mated to a permanent support infrastructure in orbit, called the motherboard. The modular satellite employs small modules, each having unique capabilities (such as communications, imagery, energy transfer, navigation, weapons etc.) able to support combat forces. Modules can perform all the functions carried out by today's independent, expensive satellites. As a result, mission capabilities increase, while lift response times shorten and operating costs decrease (Space modular systems, SpaceCast 2020).

In the car industry, engineers see modules as “a group of components which are physically close to each other, that are assembled and tested outside the firm and which can be assembled very simply onto the car”, (Warburton and Sako, 1999). In contrast, a system is defined as a coherent functional grouping. At Volkswagen, first order modules are assemblies which are installed directly in the body, such as the cockpit. Second order modules are functional systems, which together make up first order modules. Third order modules are part of second order modules... For the Golf II, an essential element of modularization was the focus on ease of assembly (Wilhelm, 1997).

Interviews conducted at HP France were also very insightful. A R&D manager reported that HP takes different approaches to product modularity. In the home computer department, modularity is really linked to standardization and subsequent externalization. For more innovative systems such as routers for telecommunication networks, modularity is related to a cognitive decomposition of R&D processes aiming at overcoming complexity. Finally, modularity is an approach taken to complete mass customization and postponement. In particular, a team is fully dedicated to search for potential common components across products, which clearly indicates a platform strategy.

On the whole, the emphasis is put on module coherence (testing, "configurability", reusability, ease of connection, externalization, knowledge...), rather than on their relative independence. Whereas it is true that a module is a stand-alone subassembly, the independence of modules appears not to have priority in industrial concerns. Indeed, the degree of module independence is not directly under firms’ control. In many industries, product complexity together with an absence of standards limits this independence. On the whole, modularity seems to be a recombining (rather than a “real” decomposition) of individual components within modules.

Linking modularity to operational strategies

Designing a modular product can have various goals. It is possible to classify these short run aims according to product life-cycle (Murray and Sako, 1999):

	Corporate objectives	Nature of product decomposition
Design	- Reduction of lead time - Fall of development costs	Platform strategy : not to redesign from scratch and better development organisation through modular design teams
	- Incremental innovation	Localization of change: products for which detailed design can be complete very quickly ("quick built products" such as software)
	- Black box design	Emphasis put on interfaces

This point has been well documented. Foss (2001) gives an account for the reduction of lead time and the fall in development cost. This is due to the fact that platform strategy enables not to redesign from scratch and thereby achieving economies of substitutions (Garud and Kumaraswamy, 1995). Also, the reuse of design knowledge creates economies of scale by spreading the costs of R&D across a great number of products. Moreover the organization of development process may be improved by setting modular teams working on each module. In particular the DSM should be used to construct a TSM (Task Structure Matrix) in order to rationalize the design process (Eppinger and al., 1999). For quick built products (Ulrich and Eppinger, op.cit) such as software, a clear distinction between general design rules and detailed design allow independent designers to be shielded from unnecessary knowledge and to focus on modular improvements. In order to achieve this, the localization of areas of likely changes is necessary.

Black box design is linked to the will of the system designer to externalize detailed design. Interfaces must then be clearly defined.

Production - General purpose	Variety at low costs	Platform strategy for product differentiation - Configurability
- Specific purposes : - Purchase and logistic	Reduction of part variety	Platform strategy leads to a decrease in the number of different parts to be purchased, transported or stocked For parts to be purchased, the sourcing of whole modules drastically reduces the number of suppliers.
- Manufacturing	- Reduction of the number of different components to be produced - Other manufacturing requirements	Platform strategy Parts requiring the same production process are clustered together
- Assembly	- Ergonomics - Facilitate and speed up final assembly - Organizing late differentiation	Localization of components in the end product and ease of connection Platform strategy
- Supply chain	- Externalization (For various reasons and in various ways)	- Core competences - Supplier competences - Emphasis put on interfaces

Here, it becomes clear that product modularization arises in a wide variety of ways. Moreover, in complex end products, several logics overlap. For example, in the aeronautic industry, modularity was adopted by Boeing in order to reduce the number of spare parts to be handled during the final assembly process (woosley, 1994). As most individual components had already been externalized, it only meant that subassembly processes were also to be externalized. The trend of module externalization is related, in the aeronautic industry as in the automotive industry, to the reduction of direct suppliers. Besides, there is also a platform logic at Boeing, Airbus, or Dassault. As a matter of fact, the instrument panel and the avionics are shared across the A/318, A/319, A/320, A/321 (Talbot and Frigant, 2002).

In the automotive industry, the decomposition was initially implemented following a subfunctional logic. This decomposition made it possible for these systems to be externalized, mainly for financial reasons. The sourcing of whole modules was linked to the reduction of first tier suppliers. Sako and Warburton (op.cit) note also that modularity was driven by ergonomic problems during the final assembly. Kinutani (op.cit) claim that modularity on the final assembly line at Mazda considerably improves work conditions and speed up final assembly. Wilhelm (op.cit) reports the Volkswagen platform strategy. The platform strategy is increasingly popular among car manufacturers. An example is the Renault Modus or the Renault Logan launched from the same platform as the Nissan Micra. Many industries, such as consumer electronics, are turning to platforms (Black&Decker power tools, Sony walkmans, HP printers, Fujitsu cameras...in Lehnerd and Meyer, 1997)

An example of manufacturing requirement is found in Mead and Conway's modularization of chips design. Thanks to a modular redesign, they allow chips to be produced by several generations of cluster tools (quoted in Baldwin and Clark, op.cit).

Finally, let us notice that modularity has become a key concept in recycling processes (Ishii, 2000). In this case product modularization should consider the ease of demanufacturing and optimal overall material recovery.

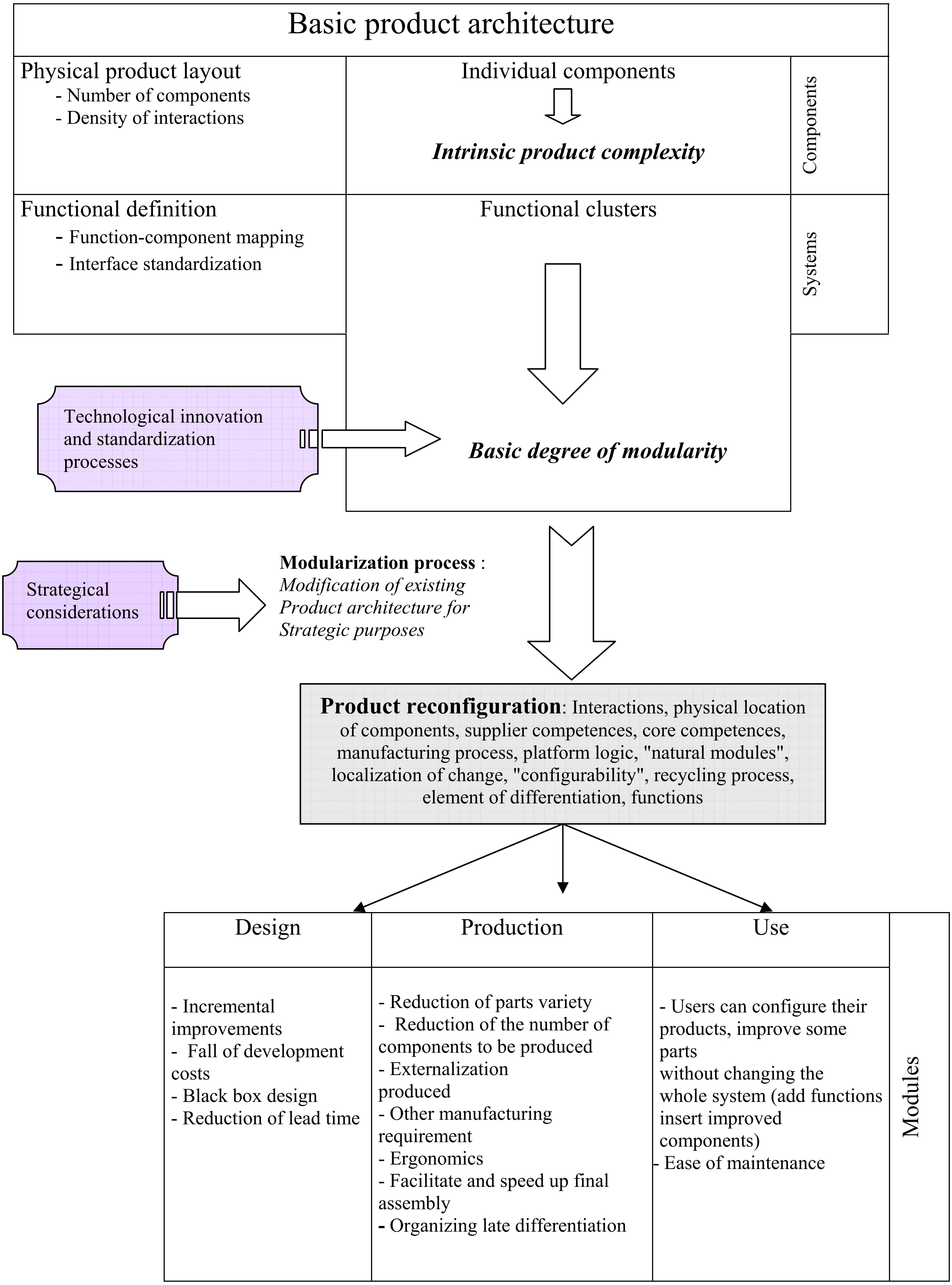
Use	**- Modularity in use :** - Users can configure their product - Users can improve their system without changing the whole system (add functionalities, insert improved components) - Ease of maintenance	- Configurability in the user perspective and ease of assembly - Functional decomposition - Localization of change - Interfaces

Here, the decomposition is carried out in the user's perspective. The question of modularity in use is related to the economic theory of network externalities. When modularity is implemented in this perspective, a critical variable is the degree to which the architecture is open (Morris and Ferguson, 1993). Examples include networked systems and complementary products such as video games.

Manufacturing machines that are modularized for questions of use in the customer's production process fall also into this category. This might be important for process intensive products such as chemicals or semiconductors. An example is found in Langlois (1998) and the modularization of cluster tools in the semiconductor industry. Other examples include packaging machines (Forcinio, 2004) and conveyors (Manufacturers' Monthly, 2004). For PCB assembly machines and more precisely placement machines, modularity is also important. As consumer products become increasingly specialized, manufacturers find their assembly lines changing from one product to another very often. This uncertainty makes it difficult for assemblers to maintain control over their equipment's utilisation. The lines that were built to serve either low-mix, high-volume or high-mix, low-volume production environments do not address the needs of today's more common high-mix, high-volume manufacturing. In this context, the movement towards modular assembly lines is gaining momentum. The benefits of a line made up of multiple "high speed flexible" modules have an immediate impact on assemblers. For instance, since each module can place the full range of component types, line balancing and optimisation is improved (The road to modular assembly, Electronics Weekly).

Principles for modular production systems have been formalized by Rogers and Botacci (1997) : "*The modular production systems concept has been proposed as a way of overcoming the limitations resulting from a lack of modular machine standards. Moreover modular production systems seek to provide a new manufacturing business framework suitable for the "agile manufacturing era". The module standards are based upon a unified reduced set of primitive elements, which are at a level of modularity lower than hitherto. The module categories comprise just four classes: process machine primitives, motion units, modular fixturing and configurable control systems. The belief is that appropriate selection from these categories will enable a diverse range of efficient, automated and integrated production systems to be built"*

Bridging the technological and strategical picture



Physical product layout
- Number of components
- Density of interactions

Individual components ⇩ ***Intrinsic product complexity***

Functional definition
- Function-component mapping
- Interface standardization

Functional clusters ⇩ ***Basic degree of modularity***

Technological innovation and standardization processes

Strategical considerations

Modularization process : *Modification of existing Product architecture for Strategic purposes*

Product reconfiguration: Interactions, physical location of components, supplier competences, core competences, manufacturing process, platform logic, "natural modules", localization of change, "configurability", recycling process, element of differentiation, functions

Design	Production	Use	
- Incremental improvements - Fall of development costs - Black box design - Reduction of lead time	- Reduction of parts variety - Reduction of the number of components to be produced - Externalization produced - Other manufacturing requirement - Ergonomics - Facilitate and speed up final assembly - Organizing late differentiation	- Users can configure their products, improve some parts without changing the whole system (add functions insert improved components) - Ease of maintenance	Modules

Our point here is to show that modularization is both a matter of technology and strategy. For simplicity we consider only three levels (components, systems and modules), but there might be many more. For instance the condenser, the evaporator and the compressor are the main components of the air conditioning system, which itself may be part of a bigger module such as the cockpit module.

Figure 2

Every product exhibits a basic degree of modularity at a given time and a given place. This degree of modularity corresponds to a given state of knowledge which has to do with the fundamental laws of physics that rule the product's functioning. It is also dependent on the current level of standardization.

To assess this level of modularity, it is fair to have a functional approach insofar as the ultimate goal of any product is to perform functions. These final functions need many other technical subfunctions to be effectively fulfilled. Functional systems are indeed often "natural" because individual components need to be integrated with others to fulfill technical functions intended to ensure the working of other functions. For instance, several component are clustered together to constitute a compressor whose function is to place hot refrigerant gas under high pressure and to drive it to the condenser where the vapor cools and returns to a liquid state. When integrated with a condenser, an evaporator...the compressor is able to provide a function to the final user.

The mapping between components and functions provides the basis for the opportunity to mix and match components to offer variety at low costs.

Economists have been obviously mostly concerned with what I have called the basic degree of product modularity. Since this degree is largely dependent on radical innovation or industry-wide standardization processes, it is not surprising that modularization has been tackled as exogenous[4]. An example of such radical innovation is the substitution of mechanical systems by electronic devices in the car architecture. For instance, multiplexing drastically reduces the number of physical connections between subsystems, making the architecture migrates towards more modularity.

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[4] We are fully aware that these radical innovations come as a result of many incremental improvements.

Figure 3

This kind of modularity, driven by innovation and standardization is really suitable for the study of technological cycles, dominant design and organizational changes. For economists, the emerging feature of modularity provides indeed an interesting field since it allows to question, in real time, the thesis of technological determinism over organizations (frigant, op.cit)

However, more often modularity is evolutionary, not revolutionary. It demands a change in philosophy as to how components are deployed and mobilized in the end product as opposed to a mere change in technology. This strategic product reconfiguration is a day-to-day concern of designers oriented towards short run and operational goals such as cost reduction. Since it consists in integrating components into more or less independent modules, it often comes to be called modularization. This process requires incremental adaptation over interfaces and therefore a great coordination between the different design teams. As it may have consequences for the subassemblies to be manufactured, it demands as well an effective coordination with production and supply chain logistic. In other words, modularization, boosted by strategic objectives, is an evolving concept (remodularization) which is rarely frozen. Given that, the question of coordination in modular systems remains open. For instance, at HP, the team in charge of identifying potential common components across products has also to analyse required adjustments and communicate them to concerned people in order to ensure coordination.

My point is not to say that there are two distinct modularization processes, I only want to make clear that modularity has different meanings. Accordingly, when managers talk about modularity it might not be in the sense that one understands. Further, there is a relationship between what I have called the basic degree of modularity and these modularization processes. Muffatto and Roveda (op.cit) find that setting a platform requires a threshold of modularity but that an excessive degree of modularity would render the platform useless.

Conclusion

This paper was motivated by the observation of a far-reaching diversity of industrial practices denominated as modularity. This diversity is not only imputable to sectorial specificities but also to strategic objectives.

Accordingly, it is possible to consider product modularization as an operational tool applied by firms to support their strategies. It means that firms can, to a certain extent, change their product architecture by recombining components within modules.

Obviously, Baldwin and Clark's vision of product decomposition (creating fully independent units) would yield many benefits. However the process of iteration along "off-diagonal interactions" (in the DSM) seems to be highly conceptual. The aim of this work was to show that there can be other, maybe more realistic, ways to modularize products. In particular it accounts for the fact that modularization arises also in complex system industries such as the automotive industry. This is another kind of modularization but it is still modularization. Further, the study of organizational consequences requires a robust approach to product modularity. We hope our collaboration with academic design engineers drove us in the right direction. Finally, it has often been said that modularity has a double dimension both technological and organizational : There might be an additional strategical dimension.

From the variety of industrial logics related to modularization, it results that the organizational outcome may not be so clear.

First, it seems that much of what has been said about modularity and vertical disintegration could be derived from the only concept of interface standardization (which is only a part of modularization). As found by Schilling and Steensma (2001), standards availability is an important element for market modularity (Chesbrough, op.cit) to arise. Second, it seems that at some points of the supply chain, there are both an horizontal consolidation and vertical integration of upstream suppliers.

Third, maybe the most common way of doing modularity (platform strategy) has no clear cut organizational consequences. According to Scania's engineers, a pre-requisite for modularity is vertical integration...

"A modular product range gives major benefits for customers in several respects. Firstly, it gives the customer almost limitless possibilities to tailor the vehicle to specific transport needs. Secondly, the availability of parts and service competence is ensured, since a limited

number of basic components is used. Ever since the 1940s, Scania's engineers have employed modularity in the design of components as well as complete vehicles. Modularity in Scania's case means ensuring that any component can be combined in as many ways as possible with neighbouring systems and components. A pre-requisite for this has been to adopt the principle of vertical integration..."

Modularity and vertical integration, Scania Group.

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