"Dynamics of Modularity. A critical approach "

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Abstract

In 1962 Herbert Simon identifies modularity as a specific configuration which improves the dynamic evolution of a complex system towards new equilibrium in the evolving context. Almost in the same period modularity is seen as a rule to be used in architectural design [Alexander 1964] to get a better fitting between a form and its context, and overcome the cognitive inadequacy of the designer. Only one year later, modularity is again proposed as the best solution to the problem of satisfying the higher variety which markets are looking for [Starr 1965]. Modularity, since these first contributions, has been thought of as the natural result or the necessary choice in the organization of complex systems, in biological studies as well as in software [Parnas 1972] and product design [Henderson and Clark 1990; Baldwin and Clark 2000; Ulrich 1995], in production [Starr 1965] as well as in organizations [Sanchez 1995; Sanchez and Mahoney 1996; Langlois and Robertson 1992; Schilling and Steensma 2001].

The focus of this paper is on discussing the modularity concept through an in-depth and critical analysis of the wide literature on the subject. The identification of three main streams of research, which most of the literature can be inserted in, will be finally used to propose a conceptual reading of the process of modularisation in its main stages and dynamics.

1. A definition of modularity

As a starting definition of modular architecture, the web site of Baldwin and Clark [2000] offers some interesting clues. " *(...) the design of IBM's 360 mainframe computer was truly modular—it was designed to have various parts, called modules. The modules were designed and produced independently of one another, but, when combined, they worked together seamlessly. As a result, all systems built out of System/360 modules could run the same software. Further, new modules could be added to the system, and old ones upgraded, without rewriting code or disrupting operations*". [**http://designRules.editthispage.com/stories/storyReader$12**]. Some parts of the definition are underlined because of their importance in identifying the most critical features of modularity.

First of all, modules are "designed and produced independently". The independence in modules design is probably the main advantage in the modular organisation of design activities. Separating a complex system into modules means that these can be designed and produced independently form each other, in separate and specialised teams. The groups work autonomously, both inside or outside the company, thanks with the "information hiding" structure of modularity.

The second point refers to the sentence: "they worked together seamlessly". Even though modules are designed separately, yet they are able to work in a coordinate way. Indeed, if the independence in the organization of design were compensated by a greater difficulty in coordinating the results singularly obtained, modularity would not be of such a great importance. The ability of modules to work together is then really important and derives from the use of a standard interfaces set.

The last three parts underlined can be discussed all together: *" all systems (...) could run the same software. Further, new modules could be added (...), and old ones upgraded, (...)*". Once again, the question is that of modules independency, both in a technical and organisational perspective. Nevertheless, they work together, sharing common resources as, in the example, a common software. This use of common parts, then, produces important savings in the resources organisation. But something more derives from the modules independency: new modules could be added and that old ones can be upgraded. As modules are independent to each other, the entire system will be updated and improved through the simple substitution of one or a few modules. The only request is that the added or upgraded module has the same standard interface so that the system can work as in the previous version, even if with higher performance.

The same web site reports a second example to explain the real nature of modularity in product design. This example is an "old-economy" shelf-book and recalls some characters already emerged in the previous part. "*A shelf is (...) a simple architecture with three flat interfaces. The modules—*

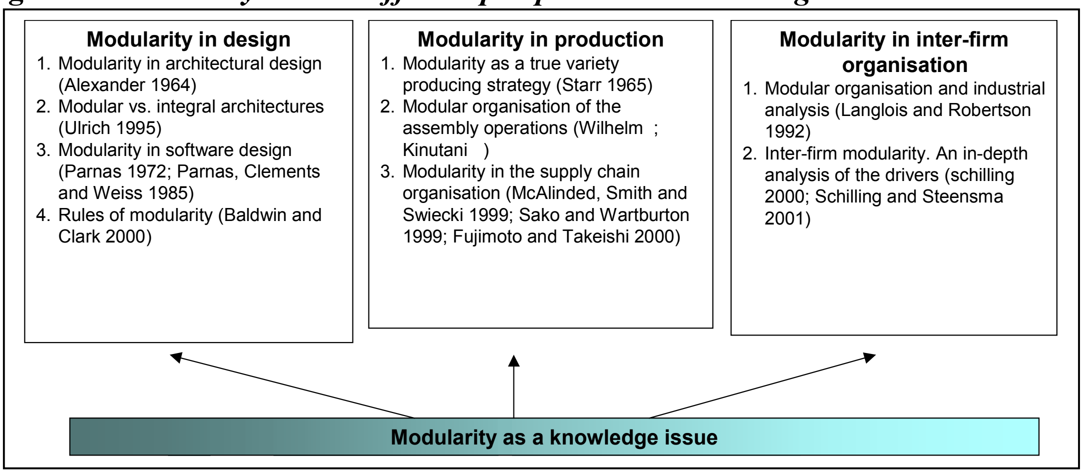
the books—fit into that space. What's important, however, is that many different books can be arranged on the shelf in a number of ways. As long as the size of the books fits into the bookshelf space, the books can be arranged alphabetically, by author, (...)". This old-fashion example remarks the increased variety which is associated with a modular architecture. The partitioning of a product into a set of modules increases the number of possible options, obtained combining a variable number of modules in many different ways. An advantage which is both for the end-user and the producer. Nevertheless, the shelf example is implicitly based on the existence of a variety limit in the shelf size: not the all books fit the shelf size. Some can be too tall or too short to be optimally located in the shelf. This means that the variety level obtained through a modular configuration is limited by the overall architecture of the system. The modular variety is the highest variety, given a certain set of standard interfaces, not the maximum possible variety.
The main modularity characters here emerged are completed by two more definitions.
As underlined in one of the most recent contributions, "*Modularity is about how parts are grouped together and about how groups of parts interact and communicate with one another*" [Langlois 2000]. Key words are here: communication, interaction and parts relation (grouping). The attention shifts from physical products to on any kind of system where these processes – of communication, interaction and relation – take place. Modularity becomes a matter of language [Langlois 2000].
Finally, modularity is a matter of degree [Shilling 2000]. A complex system can be modular at various degrees. Then, the relevant question is that of measuring the degree at which the system is modular, tracing its evolutionary trajectories towards configurations of higher or lower modularity and, most importantly, identifying the dimensions driving its temporal evolution.

2. A critical approach to modularity

2.1. From design to industrial analysis. A matter of knowledge

To better understand the concept of modularity and its growing importance in management studies, the next two paragraph present, under a critical perspective, those which can be identified as the main streams of research on modularity. These are: 1) modularity in design; 2) modularity in production; and c) modularity in inter-firm organisation.

Figure 1. ***Modularity under different perspectives. A knowledge issue***



The three "blocks" summarise most of the literature, even though we cannot find here all the "modularity contributions" but only those who have been chosen here as most significant for the discussion. On one side, each stream can be analysed separately because of the different focus on the modular question and, on the other side, a cross-analysis let us identify the common knowledge ground which they all are based on. This ground will be further specified in the final paragraph.

2.2. Modularity in design

The first stream of research is based on the analysis of modular architectures under a technical-design perspective, whose aim is to helping designers in the organisation of their activity. To summarise the many contributions on modular design, three main directories can be identified:

1. the concept of modularity applied to the specific context of architectural design [Alexander 1964], both under a static and a dynamic point of view;
2. the discussion of modular architectures, both in physical [Ulrich 1995; Ulrich and Eppinger 2000] and software products [Parnas 1972; Parnas, Clements and Weiss 1985];
3. the identification of a set of formal rules of design which can be applied to any kind of object development [Baldwin and Clark 2000].

Among one of the first contributions on modular design, the study of Alexander [1964] on modularity in architectural design is one of the most cited on modularity, together with Simon [1962]. Focused on the issue of the form design, Alexander proposes a set of principles which designers can use to create a form which is statically and dynamically consistent to its context.

The design process is a problem solving activity in which the designer faces two critical issues: a) the definition of the context (only a convention identifies the separation between the context and the form); b) the definition of the form.

A great amount of complexity and uncertainty affects this two-step process. First of all, the context can change over the time, thus asking for the adaptation of the form initially designed under different conditions. Then, even though the context does not change, the knowledge potential of the designer is limited (otherwise, the design process could have been identified as an execution activity). The search for the right solution is pursued through a process of trial and error. In the so-called "unconscious design process", the designer uses a method of progressive exclusion of inadequacy situations, from the most evident to the less relevant. This approach has a critical implication. The passage to situations which are gradually "less inadequate" could result in the acceptance of sub-optimal solutions, only because they seem to be better than the previous ones even though not optimal.

Given this situation, the modularity approach seems to be the best option.

First of all, modularity gives the designer the possibility to overcome his/her cognitive limits. Dividing the architecture in a sum of modules, each of them can be assigned to a different designer, with a specialisation of cognitive work. The prerequisite is that each module, and the designer who is assigned to it, has low or inexistent interactions with the others.

Secondly, modularity improves the consistency between the form and its context. This is true both under a static and a dynamic point of view. In a static way, a modular design makes possible the adaptation of the form to many different contexts at the same time, thanks to the substitution of one or a few modules which will change the structure with a gradual adaptation to the context. In a non-modular structure, this adaptation is impossible because the change of the form involves the rethinking of the whole architecture, each configuration being strictly specific to the specific context and idiosyncratic to the others. In a dynamic way, a modular structure can be easily and gradually adapted to the evolution of the context. Once again, this "evolving consistency" is favoured by the possibility to act on single modules.

Emphasising the positive effects of modularity, Alexander identifies a set of rules, the "conscious system" of design, organised in three stages: a) the analysis of the objective context; b) the mental representation of the designer; and c) a formal representation of form based on the use of partitions (modules). This third step represents the core of the modularisation process, in that it "objectifies" the process, creating a common language of design, and improving the results of the design process.

The second set of contributions shifts the discussion towards the ground of engineering design. The modular architecture is presented as a valid alternative to the complexity of integral architecture s[Ulrich 1985]. Products with a modular configuration, where components are mapped "one-to-one" on functionalities, has many advantages. Among the others, the possibility to: isolate the functioning of single modules, devoting each one of them to single functionalities; reduce the set of interferences which can be difficult to recognise; ease the use and manipulation of the product itself during its life cycle. This is of great help in any type of intervention, during the design phase or when repairs and modifications are needed to improve the product durability. Modular architectures are then identified as a good alternative to the integral ones where these last, probability the best possible option given a certain set of requests, are complex to manage in evolving contexts.

The software example goes deeper into the modularisation process [Parnas 1972; Parnas, Clements and Weiss 1985]. The basic aim is, again, the simplification of the software architecture through the identification of a set of modules. These modules should be simple and small enough to make the programming job easier. At the same time, interfaces should be clearly defined, so that the entire software can be easily assembled from the separate modules. Not approaching the technical side of the discussion, which analyses different rules of modularisation, the interest is towards the main effects produced by modular design [Parnas 1972; Parnas, Clements and Weiss 1985].

First of all, under a managerial point of view, modularity decreases the overall time spent in developing the software. Partitioning the software into modules which can be assigned to different designers is the way to specialise competencies, reducing the complexity faced by each designer and the time spent in designing each module. The better organization of resources results into a shorter time-to-market, increasing the possibility of competitive success.

The second advantage implied by modularity is that of greater product flexibility. The mixing and matching of modules and the overall number of configurations is made possible by the independence of modules. They can be changed, moved, and substituted independently from each other, only thanks to the respect of standard interfaces. Single interventions can be implemented using the single piece of knowledge specifically involved.

Finally, there is the cognitive dimension of flexibility. A modular structure, through its separate chunks, can be better understood, thus overcoming the lack of knowledge which affects designers. Modules should be identified in order to make the software structure simpler and easier to understand ("each module's structure should be simple enough to be understood fully" [Parnas, Clements and Weiss 1985, 260]). The specialization paradigm takes place with all the positive consequences in terms of learning and time.

These three main advantages of modularity in software design are related to the underlying hypothesis that by adding the single modules we get back the original system in its whole complexity. This is a dramatic assumption, in that it does not fully recognise the possibility of interactions, among modules, which could result from specific and not previously identified configurations assumed by the modules, thus producing unforeseen results in combining them.

The modular organisation of software design introduces two more critical issues [Parnas, Clements and Weiss 1985, 260]:

1. First of all, the modular architecture opens the way to a major change in the software structure. This evolution comes through a set of - more simple and independent - changes to the modules. This is strongly important from the knowledge point of view, because "except for interface changes, programmers changing the individual modules should not need to communicate. If the interfaces of the modules are not revised, it should be possible to run and test any combination of old and new module versions" [Parnas, Clements and Weiss 1985, 260]. But the high flexibility of a modular structure depends on the presence of some critical conditions. The product structure must be designed so that: a) the most likely changes can be implemented not involving any changes at the level of module interfaces; b) the less likely changes may involve interface changes, but only in small and not widely used modules; c) very unlikely changes can require changes in the interfaces of widely used modules, because of the exceptional nature of the event. In other words, the architecture should be carefully designed so that it could "survive" to the subsequent changes required in the evolution of the product. These changes should involve or not the interface structure, depending on how frequent are they. The choice of parameters is then a critical issue, and designers must indicate which of them are flexible and open to a wide modification and which are fixed and rigid to any change.

2. A second critical issue is the identification of the right number of modules. This should be determined so that it would not be too low neither too high. In the option of a limited number of big modules, the possibility to have unforeseen effects and interactions among modules decreases with the increase of the dimension of each of them. Nevertheless, the modules are too big to be managed. On the opposite side, having a high number of small modules increases the effects and interactions among modules. Furthermore, the implied high specialisation of competencies involved by the modest dimension and content of each module makes the knowledge structure weaker and unable to cope with those situations in which the understanding of what happens out of the module is still necessary.

The discussion opened by Parnas [1972] and Parnas et al. [1985] moves around this issue of finding a set of rules to modularise a system, identifying the right number of modules and building a system which is able to evolve consistently with its context changes. The search for modularisation rules is then related to the issue of "information hiding", which is not an easy tool. It can work at its best by letting designers focus on their job only if supported by a common ground based upon a set of interfaces and parameters which are the structure on which every module can function. This common ground is the critical part. "the use of information hiding in complex systems is practical, but only if the design begins with the writing of a module guide that is used to guide the design of the individual module interfaces. When we tried to work without the guide, numerous problems slipped between the cracks and responsibilities ended up either in two modules or in none." [Parnas, Clements and Weiss 1985, 265].

The search for a guide, emphasised in these first studies, is also the aim of Baldwin and Clark [2000], which represent the third stream of research here considered. Focusing on the computer industry, they rationalise a set of rules, the *operators*, used to explain the process of modularisation. Combined together, they give the structure a certain degree of modularity, and solve the problem of finding the way to modularise a system at its best [Parnas, Clements and Weiss 1985]. The six operators – *splitting, substituting, augmenting, excluding, inverting* and *porting* - play different roles, and have some interesting effects. A part from the first one which is devoted to modularise the structure, the other ones, one at a time or all together, introduce gradual changes in the architecture. These changes are useful both in the design and use stage. In the first case, designers take advantage from the possibility of changing the structure, gradually and incrementally, in order to find the best configuration given a set of functionalities to be implemented. In the use option, the operators realise a so-called "modularity in use" which means that a given product can be updated and improved during its life, at costs and with effects which are perfectly under control. Modularity thus increases flexibility, reduces costs of change and improves products life.

The analysis of the operators [Baldwin and Clark 2000] could be seen as the final evolution of the discussion started by Parnas, around modularity as a design issue. Under this perspective, the study of Baldwin and Clark is useful and goes deeply into the issue. Nevertheless, this perspective is based on a strong idea: that modularity can be substantially studied using a technical approach, and that organizational and strategic perspectives are a consequence of something which is under the designers control. The perspective is strongly deterministic, not considering a set of dimensions [Schilling 2000] which are probably fundamental to discuss the emerging of relevant differences in specific industrial contexts.

2.3. Modularity in production

Modularity as a production strategy has been widely studied since the '60s [Starr 1965]. To roughly classify some of the contributions proposed in literature, the discussion could be organised around two levels of analysis[1]:

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[1] A part from these two kind of studies, modular production modularity is sometimes seen as a mere consequence of modular design [Baldwin and Clark 2000]. In other words, the implementation of modular rules of design would "force" the entire system - the firm, the supply chain, the all industry - towards a modular configuration of all the processes and relations involved. This approach is then centred on a design perspective which has been already discussed.

1) a first level, in which modularity appears for the first time as a new approach to satisfy the market [Starr 1965];
2) a second level, where modularity is studied more in depth as a tendency to re-organise the production processes both inside the firm [Wilhelm 1997; Kinutani 1997] and in the supply chain [McAlinded, Smith and Swiecki 1999; Sako and Warburton 1999; Fujimoto and Takeishi 2001].

A first way to look at modularity is offered by Starr [1965]. Here modular production is considered as a new strategy to satisfy the variety request . "It is the essence of the modular concept to design, develop, and produce those parts which can be combined in the maximum number of ways". [138] Modularity, then, is the right way to deliver customers a great variety of products. Starr underlines what the marketing strategy has previously done to meet the market's requests, creating a degree of variety which is not anymore sufficient so satisfy the actual demand. Customers cannot be satisfied by what is only the product of imagination, commercials and advertisements. A new era is then opening, and modularity is the third step of a process of strategic change. The steps are:
1. control with mass production, a first stage resulting from the Ford experience, a sort of a "conquest over variability" [Starr 1965, 136] which leads to mass production; 2. product variety with mass production, a second stage still based on the mass production model, but better suited (apparently), thanks to the marketing strategy, to satisfy the greater request for variety [Starr 1965, 137]; 3.concept of modular production, a third stage in which the production process, previously conceived as a unique, is divided in two pieces. In the first one, a variety of inputs is reduced to a more limited set of modules. In the second one the process is organised to satisfy the variety request producing what Starr names "combinatorial outputs".

Starr's approach to modularity is one of the first declarations of the importance of modular production as a strategic and scientific way to produce variety, event though modularity is not technically discussed yet. The debate on modular production develops more in the '90s, mainly in the automotive industry. While in the microelectronics and software, the process of modularisation has been implemented successfully, driven by a new approach to product design, the automotive is quite peculiar. The product is complex, made of a huge amount of components which cannot be easily reduced to a limited set of modules with simplified interactions among them. But even though the car architecture is more integral and not easy to modularise, the modularity issue is quite important. The possibility to modularise the production process, with the consequent simplification of flows and relations both inside the firm and in the supply chain is strongly interesting.

The trade-off between the intrinsic complexity of the product and the aim to exploit the positive effects of a possible modularisation, produces a concept of modularity which is peculiar. In the car industry [Sako and Wartburton 1999], modularity is not based on a product architecture made of independent modules connected through standard interfaces. The discussion on modular production focuses more on the organisation of the production processes, first of all in the assembler firm (as in Wolkswagen [Wilhelm 1997] and Mazda [Kinutani 1997]). At the earth of the debate there is the attempt to modularise the assembling process, finding the optimal organisation of flows and resources, almost independently from the architecture of the product. As reported in McAlinded et al. [McAlinded, Smith and Swiecki 1999], modularity can be defined at two different levels where the first one, that of assembling modules, is simply "the practice of shifting subassembly lines that manufacture modules next to the final vehicle assembly line to separate supplier facilities at some distance from the plant" [McAlinded, Smith and Swiecki 1999, 1]. At this stage, there is no need to modify the design rules or the module content. At a second stage, modularity can have stronger implications when modules are explicitly designed so that they are "optimised at the final assembly level by independent suppliers" [McAlinded, Smith and Swiecki 1999, 1]. In this situation, the adoption of a modular approach must be supported by new design rules and, consequently, new supply relations. Mainly referred to this last approach, some possible improvements are emphasised. First of all, a higher flexibility supported by the possibility to rapidly change the product configurations mixing and matching the modules. Furthermore, suppliers can focus more on internal technical innovations, not worrying about the general product architecture. A second advantage is related to gains in speed and expanded design capability as already emphasised in the design approach. Using the modules as basic components, the production time is reduced, fastening the response to customers. The last advantage is that of cost reduction, which means savings in terms of labour costs (those of the suppliers), reduced engineering efforts, lower materials costs (for the assemblers), scale economies and lower investments.

In summary, the specialisation of competences between component suppliers and vehicle producers - the first ones focused on modules production and the second ones on the organization of the car assembly – is a rational rethinking of the assembly process aimed to reduce time and costs, more than a consequence driven by a dramatically new approach to design. The positive portrait of modular assembly does not explicitly consider some critical side-effects. Among the others, the increasing rigidity of a process where the modules organisation must perfectly fit the schedule, not leaving room to the absorption of unforeseen changes. What if the coordination among modules does not work perfectly? Shall we attend the system to collapse? What kind of flexibility tools can be introduced in the system? Shall we try to eliminate all of these events, with a tighter control over the system? Does the elimination of unpredictable events, eventually disturbing the system, require a deep re-organisation of the supply chain, with the definition of new supply expertises?

A more problematic perspective on modular production, with a complete analysis of the supply chain implications, is offered by some recent contributions [Sako and Warburton 1999; Fujimoto and Takeishi 2001]. Here modularisation is fully seen in its double perspective, from the point of view of both the final assembler and the supplier. As to the final assembler, modularisation is the way to get higher efficiency. The simplification of the assembly process under an ergonomic point of view (incorporating pre-assembled parts into the line), the support of technological competitiveness of external suppliers, the reduction of costs and assets otherwise increased by strategies of internal production explain why to modularise and outsource [Sako and Warburton 1999]. On the supplier front side, the main motivations are: the search for a growth and, put in another way, the attempt not to be marginalized (in the event the supplier would be unable to satisfy the request for a "complete supply" of modules).

The combination of these aims produces a trajectory of modularisation which is strongly influencing the evolution of the automotive industry in its whole. As a result, the European and American automotive industries live an age of growing outsourcing, with a re-organisation of the supply chain where the best suppliers specialise themselves in the supply of pre-tested, high quality, complex systems. The organisation of the market, nevertheless, is not modular in a proper way. Modules are common to a small number of models of the same brand. No room is left for modules shared among different lines and companies and the system is still hierarchically organised and controlled by the final assemblers.

Some new points of discussion are finally offered by Fujimoto and Takeishi [2001], with the analysis of the eventual overlapping between knowledge and task partitioning and its effects on the performance of the organisation of the supply chain.

2.4. Modularity and industrial analysis

The question of modularity plays a critical role also in the analysis of inter-firms organisation at the industry level.

Empirical evidences emphasise the emerging of modular trajectories in many industries [Langlois and Robertson 1992; Baldwin and Clark 2001; Brusoni and Prencipe 2001], but not in all of them.

The analysis does not only differ in terms of evolutionary trajectories, but also in terms of approaches used to analyze the different trends. As already underlined in the discussion of modular design, the modularisation of an industry can be perceived as the unavoidable result of a set of technical rules [Baldwin and Clark 2000]. These rules, applied to the micro level of labor organization, tend to replicate the same organizational pattern at the macro level of industry organization, following a process which seems to be deterministic. The in-depth discussion of these rules, to understand why the organizational system (the firm and the market as a complex) should adopt modular configurations is based on the strong assumption that the all trajectory is explained by a simple process of expansion from a micro to a macro level, not giving any explanation of why some industries do not adopt a modular organization.

A second approach considers the modularity as the effect of interacting conditions both on the demand and supply side [Langlois and Robertson 1992]. As in the case of high fidelity-stereo system and microcomputer industries, the variables used to explain the process of modularization are, on the supply side, the entity of production and transaction costs and, on the demand side, the attributes which consumers want. "…the nature of what consumers believe is the essence of a given product often changes. Consumers may add certain attributes and drop others, or they may combine the product with another product that had been generally regarded as distinct. Alternatively, a product that consumers had treated as an entity may be divided into a group of sub-products that consumers can arrange into various combinations according to their personal preferences. We call this kind of network of sub-products a *modular system*" [Langlois and Robertson 1992, 297]. The reasons why modularity arises as the best match between the two sides of the market are then a combination of both low transaction costs and high scale economies. When the consumer costs of knowing and deciding how to combine the modules are low, and producers gain economies of scale in assembling pre-packaged modules, a modular network arises. The combination of supply/demand costs and benefits must be finally considered in connection with the life-cycle stage of the product.

The identification of the driving forces is further discussed by Schilling [2000], whose aim to propose a theory of modularity passes through the identification of those dimensions which moves a system along an ideal trajectory. Reaching a state of higher or lower modularity is then the effect of a set of forces, whose dynamics add to each other determining the architecture of the system. The assumptions of the model are:

1. as already emphasised in the paper, each system must be fitted to its context [Simon 1962; Alexander 1964];
2. given this aim, modularity is a matter of degree. Any kind of system is somehow modular if this condition is consistent with the aim to increase the fitness to the context. Thus modularity is a pervasive condition;
3. given the variable nature of modularity, the real question is: what are the forces driving a system along its trajectory towards positions of higher or lower modularity? The answer to this question can be used to build a theory of modularity which could be useful in discussing the evolution of any kind of system (a product, an organisation, a problem solving structure).

The resulting framework is built on a set of forces which are positively correlated to modularity and opposed by a natural inertia which lowers the speed of the modular trajectory. Some of the driving forces, the heterogeneity of demands and inputs, act directly and positively on the trajectory of the system. Other two dimensions, urgency and synergistic specificity, act indirectly, reinforcing or contrasting the trajectory of the system. The all forces, driving the system in its search of fitness with the context, are finally contrasted by the natural inertia which slows down the process.

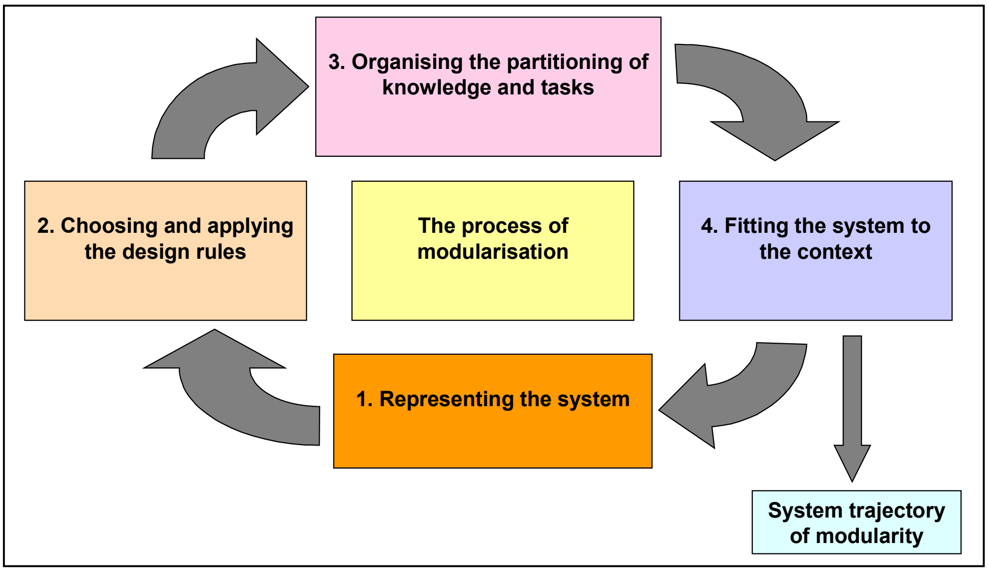
This framework is an interesting attempt to identify the dynamics of modular systems, even with some criticalities. Among the others, the absence of a clear discussion of the role played by the technological change. Even with all the dimensions driving an industry towards a modular organisation, one can suppose that when the technology is still in a stage of rapid evolution, with an unclear definition of the technological platform, the choice of a modular organisation would be inadequate for the risk involved in investing in an architecture which is still "in process", thus asking for a continuous adaptation of the operators and their competence investments.

This model is further developed [Schilling and Steensma 2001] and applied to the analysis of modularity in organisational forms, deepening a discussion which goes well over the technological ground [Langlois 1999; Koppel and Langlois 2000].

3. The process of modularisation. A proposal

This final part of the paper aims to propose a representation of the dynamics of the modularisation process, as emerging from the critical analysis of the literature previously offered. The figure 1, where all the contributions on modularity have been analysed emphasising their knowledge content, can be then completed by figure 2. Here the process of modularisation is identified as a four stages process.

Figure 2. The process of modularisation: a knowledge perspective



The steps are:

1. representing the system.;
2. choosing and applying the design rules;
3. organising the partitioning of knowledge and tasks;
4. fitting the system to the context.

The first step, of representing the system, identifies the process of problem conceptual representation. Here the decisional subject, "the designer", traces down a description, analytical and graphical, of the problem: an physical artefact [Baldwin and Clark 2000], an architectural project [Alexander 1964], a software [Parnas 1972; Parnas, Clements and Weiss 1985] or any kind of complex system [Simon 1962; Schilling 2000] which is described in its main *functionalities*, *components* and *relations*. This first representation is influenced by the subjectivity of the designer - previous experience and aims – as well as by the purposes of the project. nevertheless, it also represents the system in its whole complexity and entirety, not choosing a specific architectural pattern.

The second step, of choosing and applying the design rules, is grounded on the choice and application of a set of rules of design. These are used to modularise the artefact or the problem [Baldwin and Clark 2000; Alexander 1964; Parnas 1972; Parnas, Clements and Weiss 1985], and plays a critical role in the identification of the possible solution found out. As Parnas points out [1972], the possible architectural configurations, though all modular, can be different, and the application of a set of rules implies the identification of only one option, among the many possible, thus excluding the remaining ones. While in the first step the subjectivity of the process is connected to the subjective representation of the designer, in this second step the result depends on the choice of the specific set of modularity rules.

The third step, of organising the partitioning of knowledge and tasks, is the execution of the pattern emerged at the end of the first two steps. It uses the conceptual inputs of the second step and finds out a consistent pattern of knowledge and task organisation. At a micro level, it produces a specific organisation of the cognitive labour inside the organisation (the design and development group, the single firm in her whole) [Henderson and Clark 1990; Sanchez and Mahoney 1996]. At a macro level, the organisation of labour extends to the partitioning of knowledge and tasks (of design and production) among the many actors of the supply chain [Fujimoto and Takeishi 2001; Sako and Warburton 1999]. This process, then, plays a key role in connecting the conceptual framework of modularity as a problem solving rule to the organisation and division of knowledge and competencies at a level of supply chain and industry.

The process of modularisation ends with the final step, of fitting the system to the context. The organisation, both conceptual and practical, emerging from the previous step, verifies its fitting to the context [Alexander 1964], and produces a trajectory of increasing or decreasing modularity [Schilling 2000]. This trajectory results from the combination of the pattern of modularity previously chosen with the drivers [Schilling 20001] operating in the specific context in which this pattern must be applied. If the modular configuration of the system fits the context, the degree of modularity increases, otherwise the system will find a different condition, of lower modularity. This last step then connects the inner process of modular representation and design with the external process of fitting between the designed system and its context dimensions.

4. Conclusions

The four-steps process here described lets some interesting points emerge:

1. first of all, the process of modularisation is strongly path-dependent. Starting from the first step and going on with the following ones, the process of modularisation is forced to follow a course which is strictly dependent on the previous decisions, the great part of them influenced by subjective choices;
2. the process in its whole is subjected to the initial ignorance of the real condition of the system. This absence of a complete knowledge explains the variety of possible configurations which the designers can choose among and has a strong implications on the final solution. This can differ, at various degrees, from the optimum, simply because it cannot see and know it [Delaini, Legrenzi, Marengo, Orsenigo 2000; Egidi 2000];
3. the first two steps of the process have a critical importance in that they are conceptual, defining the framework of representation and organisation of the system which will be further developed in the two subsequent steps of execution;
4. the modularisation tries to put together a "resources based view" of the firm [Barney 1991], putting in evidence the knowledge and competence content of the process, and an industrial view, considering the influence of those drivers, both internal and external to the firm [Schilling 2000] which move the system in its trajectory of modularity;
5. finally, the process is inherently dynamic, considering the feedback from the competitive environment to the system architecture which would result in a repetition of the process of modularisation.

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