

Towards a contribution to modularity concepts and principal domains

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Abstract: Modularity concept emerged in the 1960's within the computer industrial sector, bringing considerable competitive advantages and benefits. Since this period, modular approach has been applied in many industrial sectors, such as automotive, electronics, furniture and others. In this sense, this study examined papers regarding modularity and their applications in the industrial and organizational perspectives, towards a concept better understanding and context where it is applied. A theoretical-conceptual paper was carried out through a hypothetical-deductive method to analyze the publications. Results show similarities and discrepancies among modularity concept variations. In addition, it was perceived that automotive industry has been solely using modularity in design, production and use. Lastly, benefits, difficulties and recommendations were identified in the modular approach adoption. Thus, it can be concluded that a difficult still remains in defining a unique and broad modularity concept, due to variants according to the modularity approach (design, production, organizational, etc.) utilized. Future studies should search for a better understanding about variations of modularity concept, trying to find what characteristics are predominant throughout all concept variants.

Keywords: modularity, modularity in design, modularity in production, modularity in use, organizational modularity.

1. Introduction

Modularity concept has been widely utilized since the beginning of the 21st Century. However, the concept emerged before, in the 1960's within computer industry, bringing competitive benefits and demonstrating significant importance in the product development process (ARNHEITER; HARREN, 2006). Besides, modularity helps designers and engineers in the development of products which have potential to comply with different markets (CARDOSO; KISTMANN, 2008). During the past years, companies are increasingly forced to optimize their resources, adapt themselves to the global market dynamics and satisfy consumers, which are getting more demanding due to a broad access to information. In this context, one of the strategies that helps to improve product and process quality is modularity, which aims to (BALDWIN; CLARK, 2004; CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011): facilitate the management of complex products and processes through the division into simpler modules; enable parallel production activities, since modules can be manufactured simultaneously; and adapt production to future uncertainties, because the final product might be modified by adjustment of a single module or component, requiring a lower cost than redo the whole product.

As mentioned earlier, modular products are designed as a set of independent and simpler modules, which can be reused and interchanged to maximize product variety (STARR, 1965). Thus, modular products supports standardization that facilitates (re)manufacturing, helps to

eliminate waste, and decreases costs. In addition, modularity is an attribute of a complex system that advocates designing structures based on reducing interdependence between modules and maximizing interdependence within them that can be mixed and matched in order to obtain new configurations without loss of functionality or performance in the system (LANGLOIS, 1992; BALDWIN; CLARK, 1997; CAMPAGNOLO; CAMUFFO, 2010). In other words, modularity has many facets starting with interchangeability of parts (STARR, 2010). According to the previous author, modularity varieties stem from different concept applications of units of interchangeability.

During the past decades, modularity attracted the attention of numerous management scholars (CAMPAGNOLO; CAMUFFO, 2010). In addition, authors have been studied the subject in several perspectives: product modularity (CARIDI; PERO; SIANESI, 2012; HUANG et al., 2012; LAU; YAM; TANG, 2011), process modularity (PARENTE; BAACK; HAHN, 2011; JACOBS et al., 2011), service modularity (GEUM; KWAK; PARK, 2012; LIN; PEKKARINEN, 2011; BASK et al., 2011) and/or production modularity (RODRIGUES; CARNEVALLI; CAUCHICK MIGUEL, 2009; DORAN et al., 2007) as well as the impact on the final products quality (LAU; YAM; TANG, 2009), critical factors in the modular product management (LAU; YAM; TANG, 2010) and competitive advantages through the modular strategy adoption (JACOBS; VICKERY; DROGE, 2007).

However, although modularity has been a popular concept especially in operations research and management for decades, no universal definition of modularity seems to exist (BASK et al., 2010). Therefore, the objective of this paper is to systematically examine studies about modularity and its applications in the industrial and organizational context, dealing with different facets of modularity. Relevant concepts were identified and discussed. An initial conceptual framework highlighting the modularity concept is derived based on this literature analysis. The remainder of this paper is structured as follows: section 2 presents the research method. Section 3 provides the theoretical basis on modularity by expressing its main concepts and types of modularity (used for literature classification). Section 4 presents the research issues on modularity including findings from the literature review and, finally, section 5 draws some concluding remarks and main implications of this work as well as the next steps of this research project.

2. Research methods

This paper is classified as a theoretical study (BERTO; NAKANO, 2000; CAUCHICK MIGUEL, 2010) based on a systematic literature review. It is essential to any research proposal that the subject is defined and understood, which involves identifying the current theoretical state of the art. Moreover, the objective of a literature study is not merely to group authors and publications. In fact, main purposes include the identification of gaps in the literature as well as dominant research methodologies associated with the chosen research subject.

In this sense, this paper employs a systematic literature review, firstly using keywords in data bases such as ISI Web of Knowledge, Scopus, Compendex and SciELO to retrieve articles regarding the topic “modularity”. After that, each article was examined in order to identify main aspects that involves modularity (i.e. the main issues discussed in the article), industrial sector, and taxonomy related to modularity. It is worth stressing that this paper does not describe the contents of each examined paper. Nevertheless, the concept of the studied subject (i.e. modularity) is outlined as well as its types aiming at identifying important issues

concerning the taxonomy. The bibliographical sources that were used in this paper are mainly publications in leading referred journals.

A literature review can be categorized according the following criteria (NORONHA; FERREIRA, 2000): purpose (analytical or supportive – as is suitable to thesis, dissertations, etc.), scope (thematic or time-based), function (historical or for updating), and approach (critical or bibliographical). Table 1 shows how this paper is categorized according to the previous criteria in addition to the rationale for this classification.

Publications of interest were identified and retrieved from various data bases, e.g. ISI Web of Knowledge, Emerald, SciELO (Scientific Electronic Library Online), etc. EndNote® software was used to record and organize the references. Each article was individually and electronic recorded for further analysis.

3. Modularity – Terms and definitions of a multi-concept

The term modularity is familiar to industry and academia, but often is not clearly understood because of its broad interpretation (ISHII; WANG, 2003). In fact, there are a number of terms that is used to describe modularity, showed in Table 2.

There are several modularity definitions in literature (ULRICH, 1995), thus it can be considered as a multifaceted concept (BALDWIN; CLARK, 2000). Even the definition of modularity was in question for a while, as in Gershenson, Prasad and Zhang (2003). A major reason for this problem is that modularity definitions come in different perspectives (FIXSON, 2005) and heterogeneity stymies systemization (STARR, 2010). Starr (2010) puts forward that modularity, in spite of its age, is a splintered concept with a variety of inchoate offshoots (certainly not well-organized). The author says that splintering occurred slowly but surely as (over almost 50 years) a great number of constituencies defined and applied modularity to their own spheres of interest.

Another reason that may influence on the difficulties to define a generic concept of modularity is because there has been little effort made to reach a consensus on the definition of this term and its appropriate use (GERSHENSON;

Table 1. Classification of the literature review in this paper.

| Classification | Type | Definition | Rationale |
|----------------|--------------|--|---|
| Purpose | Analytical | Proposes a group of various issues in a subject and specific chosen topic | Identify existing publications of taxonomy on modularity |
| Scope | Thematic | Presents a specific and in-depth description about a chosen topic | Identify the state of the art of current modularity theory |
| Function | For updating | Describes most relevant literature recently published development of knowledge | Identify most publications that deal with modularity concepts |
| Approach | Critical | Provides a reflection on the chosen topic | Establish a theoretical map concerning issues on taxonomy |

Source: Developed by the authors based on Noronha and Ferreira (2000).

PRASAD; ZHANG, 2003). This state of affairs is shocking because when first elucidated, the modularity concept seemed to be simple and straightforward (STARR, 2010). In addition, Campagnolo and Camuffo (2010) stated that modularity broad-based appeal has generated some controversies and ambiguities on how modularity should be defined, measured and used in managerially meaningful ways. In their study, they found that this ambiguity impedes rigorous empirical studies capable of understanding the relationship between modularity in product, in production and in organization design. Nevertheless, successful applications exist. Some of those aspects are discussed next.

3.1. The concept of modularity

For human beings, the only way to manage a complex system or solve a complex problem is to break it up (BALDWIN; CLARK, 2000). Modularity is an approach for organizing complex products and process efficiently (BALDWIN; CLARK, 1997) by decomposing complex tasks

into simpler portions so they can be managed independently (MIKKOLA, 2001b). Modularity should also be defined as interchangeability of alternative substitutable parts or materials of a product (STARR, 2010). The development of interchangeability and standardization of parts were in many ways the modularity precursors (ARNHEITER; HARREN, 2006). In this sense, modularity arises from the decomposition of a product into subassemblies and components (GERSHENSON; PRASAD; ZHANG, 2003). In the literature, two different emphases when defining modularity (see Table 3) are frequently used (BALDWIN; CLARK, 1997; ULRICH, 1995; ULRICH; TUNG, 1991).

Ulrich and Tung (1991) and Ulrich (1995) definitions are that modularity is the relationship between a product's functional and physical structures such that there is a one-to-one or many-to-one correspondence between the functional and physical structures and unintended interactions between modules are minimized. These definitions were built in different applications of the concept. The authors (ULRICH, 1995; ULRICH; TUNG, 1991) were in the context of product architectures based on the relationships between the function and physical structures. In their work, Baldwin and Clark (2000) particularly focus on products and processes and they state that it is difficult to establish a definition of modularity on function, which are inherently manifold and non-stationary. Therefore, Baldwin and Clark (1997) definition's of modularity is based on relationships among physical structures, not functions. Hence, Baldwin and Clark (1997) define modularity as building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole.

Table 2. Terms on Modularity.

| Terms | References |
|------------------------------|--|
| Modular components | Sanchez and Mahoney (1996) and Shaefer (1999) |
| Modular innovation | Henderson and Clark (1990), Christensen and Rosenbloom (1995) and Hsuan (1999) |
| Modular product architecture | Ulrich and Eppinger (1995), Sanchez and Mahoney (1996) and Lundqvist et al. (1996) |
| Modular system | Langlois and Robertson (1992) and Baldwin and Clark (1997) |

Source: constructed based on Mikkola (2001a).

Table 3. Emphasis of most cited modularity concepts.

| Emphasis | Publications | Sector (product) where the concept were applied |
|--|--|--|
| Physical structure (BALDWIN; CLARK, 1997) | Doran (2003, 2004, 2005) | Automotive (Supply chain) |
| | Fredriksson (2006) | Automotive (Modular assembly processes) |
| | Blecker and Abdelkafi (2005) | Personal Computer (PC) |
| | Bask et al. (2010) | Logistics Services |
| | Jose and Tollenaere (2005) | Different products families (design using platform concept) |
| | Caridi, Pero and Sianesi (2012) | Furniture industry |
| | Asan, Polat and Serdar (2004) | Electronic Products (Domestic gas detector product family) |
| | Miozzo and Grimshaw (2005) | Information Technology Outsourcing |
| Function (ULRICH; TUNG, 1991; ULRICH, 1995) | Voordijk, Meijboom and Haan (2006) | Construction industry |
| | Fredriksson (2006) | Automotive (Modular assembly processes) |
| | Blecker and Abdelkafi (2005) | Personal Computer (PC) |
| | Jiao and Tseng (2000) | Electronic products (e.g. as telephone switching PBX, stereo equipment, computers and instrumentation) |
| | Bask et al. (2010) | Logistics Services |
| | Lau, Yam and Tang (2007) | Supply Chain Management in Manufacturing Industry |
| | Jose and Tollenaere (2005) | Different products families (design using platform concept) |
| Brusoni and Prencipe (2001) | Aircraft Engine and Chemical Engineering | |

Source: Developed by the authors (2012).

In fact, more than 10 years ago, the majority of modularity studies was related to functional modularity (SIDDIQUE; ROSEN, 1998) and in recent years is still in this way. There is a clear consensus on the point of form and function independence (GERSHENSON; PRASAD; ZHANG, 2003). On the words of Gershenson, Prasad and Zhang (2003) the roots of modularity definitely lie in the form-function relationship and most publications treat it as such. By analyzing Table 3, it is not possible to draw a conclusion on the most suitable definition of modularity for an industrial sector or product. Some authors such as Fredriksson (2006), Blecker and Abdelkafi (2005), Bask et al. (2010) and Jose and Tollenaere (2005) use both definitions to support their work despite the differences among the industrial sectors studied. However, when a publication deals with modular product development, Ulrich (1995) and Ulrich and Tung (1991) definition are commonly adopted as it can be observed in the Jiao and Tseng (2000) study.

Besides the definition of modularity based on form and/or function, some other definitions look on the term “independence” as fundamental. Independence and functional independence have dominated the modularity discussions and the element of independence is at the core of the intent in modular design (GERSHENSON; PRASAD; ZHANG, 2003). Chen, Navin-Chandra and Prinz (1994) propose modularity based upon the ‘relationship between achieving functional independence and reducing the interactions between modules’. Modularity in general aims at packaging individual functionalities in a way that functionalities in one module would have as much in common as possible and that those modules would be as reusable as possible (TSAI; WANG, 1999). The functional independency significance is that it may facilitate the extension and configuration of modules. This is very important for the product family development. The principle of functional independency implies that there should be ideally a one-to-one mapping between sub-functions and modules (ULRICH, 1995).

Bask et al. (2010) present their own summary of the literature review, defining a modular system as a system built of components, where the structure of the system, functions of components and relations of the components can be described so that the system is replicable, the components are replaceable, and the system is manageable. Others authors use the benefits or the usability to define the term. In the past, modularity was defined by Walz (1980) as constructed of standardized units of dimensions for flexibility and variety in use. Therefore, broadly defined, modularity is the use of modules to facilitate assembly and customized configuration of finished products, it can be used to simplify and facilitate the design of production systems as well as products (ARNHEITER; HARREN, 2006; CARIDI;

PERO; SIANESI, 2012). Huang and Kusiak (1998) refer to modularity as the use of common units to create product variants. It can be defined as using sets of units designed to be arranged or joined in a variety of ways (CIVIL..., 1996).

Modularity is also a concept present in other knowledge fields. In software design, modularity usually refers to instruments which are made to build large programs out of pieces by the user (CHEN, 1987). Modularity in art has been defined by Jablan (1997) as the use of several basic modules for constructing large collection of different structures. An example would be bricks in architecture or in ornamental brickwork. The previous author states that modularity principle is a universal economy of nature principle, which allows diversity and variability from a combination of a few basic elements. Schilling (2003) considers modularity in the general case without restrictions concerning the kind of system, defining modularity as a general systems concept: it is a continuum describing the degree to which a system’s components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the “rules” of the system architecture enable (or prohibit) the mixing and matching of components. Blecker and Abdelkafi (2006) – for the purpose of their work where the subject was “complexity and variety in mass customization system” – define modularity as an attribute of the product system that characterizes the ability to mix and match independent and interchangeable product building blocks with standardized interfaces in order to create product variants. The objective of mapping between functional elements and physical building blocks is preferable and refers to an extreme and ideal form of modularity.

Within all those definitions, they just account for modularity form, function, independence, usability or benefits. However, with the growing environmental pressure the definition must be extended beyond all this concerns across the product life-cycle and the benefits that modularity can achieve with it. A term that comes with product life-cycle is similar. For example, for more than one decade, Gershenson, Prasad and Allamneni (1999) define life-cycle modularity as modules and interactions that arise from the various processes the components undergo during their life-cycle including development, testing, manufacturing, assembly, packaging, shipping, service, retirement, and so on. Newcomb, Bras and Rosen (1996) study is based on their hypotheses that product architecture is the governing force in life-cycle design and that more modularity is better in all life-cycle viewpoints.

As can be seen, there is not a clear consensus on the definition of modularity and the publications usually use the term pointing to the type of work. Nevertheless, in order to enhance the understanding of modularity, it is necessary to define what a module is.

3.2. Module definition

A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units as quoted by Baldwin and Clark (2000). Moreover, a module is described as a set of components (NEWCOMB; BRAS; ROSEN, 1996). One can think of a module as a self-contained subassembly that connects to other modules using common interfaces (ARNHEITER; HARREN, 2006). Clearly there are degrees of connection, thus there are graduations of modularity (BALDWIN; CLARK, 2000). As defined by Allen and Carlson-Skalak (1998), a module is a component or group of components that can be removed from the product non-destructively as a unit, which provides a unique basic function necessary for the product to operate as desired. Going into more details, Marshall, Leaney and Botterell (1998) describe modules as having the following characteristics:

- They are co-operative subsystems that form products, manufacturing systems, and so on;
- Functional interactions occur within rather than between modules;
- They have one or more well-defined functions that can be tested in isolation from the system and are a composite of components of the module; and
- They are independent and self-contained and can be combined and configured with other modules to achieve overall function.

Modules can include a wide range of value-added content and complexity ranging from simple and disposable modules such as ballpoint pen refills to larger complex modules like automobile chassis. By increasing the size and complexity of each module, it is possible to greatly simplify the supply network by reducing a product containing thousands of individual parts to a handful of subassemblies (ARNHEITER; HARREN, 2006). In an ideal module, each component is independent of all components not contained in that module throughout the entire product life-cycle (independence). In addition, each component in the module is processed in a similar manner during each life-cycle stage (similarity) (GERSHENSON; PRASAD, 1997).

3.3. Modularity principal domains

As mentioned earlier, modularity can be considered as a multifaceted concept (BALDWIN; CLARK, 2000) and modularity definitions come in different perspectives (FIXSON, 2005). Hence, literature usually groups modularity concept in three principal domains, namely: modularity in design, modularity in production, and modularity in organization (SAKO; MURRAY, 2000; CAMUFFO, 2001; DORAN, 2003) or modularity in organization and supply chain (BASK et al., 2010). In

addition, other authors also consider modularity in use (SAKO; MURRAY, 2000; CARDOSO; KISTMANN, 2008; PANDREMENOS et al., 2009) as well as modularity in services (BASK et al., 2010; GEUM; KWAK; PARK, 2012).

3.3.1 Modularity in design

Modularity in design has been investigated to reduce design process complexity (ULRICH; EPPINGER, 1995; FUJITA, 2002). Modularity in design can be, therefore, defined as choosing the design boundaries of a product and of its components, i.e. on how to divide a system into modules, so that the design features and tasks are interdependent within and independent across modules (HUANG; KUSIAK, 1998; CAMUFFO, 2001).

Ulrich (1995) analyzed the structures of design, in terms of product structure, physical functions, etc. and distinguished them into modular architecture and integral architecture. According to Fujita (2002), the former indicates a one-to-one mapping from functional elements in a function structure to physical components of a product and decoupled interfaces among components. The latter indicates a complex (not one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components. An important task in product architecture is to find common modules across products for “platforming” a product family or to find a common module for joint development with a partner. In this sense, Fujita (2002) developed a five-step algorithm to group functions into modules and choose from different candidates to form a good platform. The algorithm accomplishes this task of grouping and creating a dendrogram which is applied to a group of four products. Aiming to provide a taxonomy on modularity, Bi and Zhang (2001) state that there are two basic categories of activities involved in modularity design:

- Product modularity: it should result in an architecture of a product such that the product can be made by simply assembling pre-existing components. To realize it, product functions, product life cycle issues and costs should be considered;
- Task-oriented determination of modular configuration: it is described by O’Grady and Liang (1998, p. 269) as: “[...] given a set of candidates modules, produce a design that is composed of a subset of the candidate modules and which satisfies both a set of functional requirements and a set of constraints [...]”.

Bi and Zhang (2001) provide more details on those categories by deploying them in issues showed in Table 4. The authors also state that both product modularity and determination of modular configuration involve design evaluation, which can be performed from different viewpoints: function, flexibility, cost-effect, environment, technique, and complexity.

Table 4. Issues in design modularity.

| Product modularity | Modular configuration determination |
|---------------------------------------|--|
| Identification of requirements | Architecture and requirements description |
| Determination of modular architecture | Determination of a sub-problem |
| Module design | Constraints and objectives coordination |
| | Determination of interfaces and internal variables |

Source: Constructed based on Bi and Zhang (2001).

Automotive firms, for instance, usually employ modularity in design. Fredriksson (2002) cites Mercer (1995) and McAlinden et al. (1999) to exemplify that typical car modules on the highest level in the product structure are: seats, cockpits, front-ends, headliners, door panels, fuel tanks, etc., which all contain variant specific components.

3.3.2 Modularity in production

Modularity in production means choosing plant design boundaries to facilitate both manufacturing and assembly to meet product variety, production flow, cost and quality requirements (CAMUFFO, 2001). In this direction, there are now commercial equipments for enabling and facilitating the introduction of modular plants. A ‘component-based automation’ solution is supplied to a modular plant at VW in Wolfsburg, Germany (SIEMENS, 2004). It is a solution for the factory paint shop; a decentralized automation approach in which intelligence is distributed to technological modules that combine logically mechanics, electrical functions, and control program. The technological modules include robots, filling machines and other parts of a production plant (SIEMENS, 2004).

In addition, modularity in production also refers to apply sub-assembly, pre-fitment testing of modules and transferring some of these activities to suppliers (DORAN, 2003). The influence of modularization on the factory floor lies in the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then brought onto the main assembly line and incorporated through a small and simple series of tasks (SAKO; MURRAY, 2000). In this sense, Fredriksson (2002) analyses the conditions provided for module assembly units performance through a case study conducted at Volvo. It considers pre-assembly and outsourcing. The paper also shows that organizational forms (ownership and location) provide different conditions for module assembly units performance; the modularity in organization is further discussed in the next section.

For example, many automakers such as GM, Fiat, Ford, Daimler-Chrysler, Mercedes Benz, and VW have

experienced with modular assembly plants in the past years (CAMUFFO, 2001). Volkswagen was the first plant to apply modularity concepts extensively, specifically at its plants in Resende in Brazil, Boleslav in Czech Republic and Mosel in Germany (MARX; SALERNO; ZILBOVICIUS, 1997). Ford and GM have built new plants that specifically accommodate modular assembly (DORAN, 2003).

3.3.3 Modularity in organization

Modularity in organization relates to the organizational process, governance structures and contracting procedures that are adopted or used to accommodate modular production at both the intra and inter-firm context (DORAN, 2003). For instance, Camuffo (2001) presents a case study of the roll-out of a Fiat world car in a field work carried out in 6 countries. In this study, the author examined aspects of modularity, outsourcing, and globalization to find out if there was a relationship among them. The case study pointed out that, at the firm level, those concepts are linked. Outsourcing and modularity, though increasingly inseparable and overlapped in practice, remain conceptually distinct (CAMUFFO, 2001).

3.3.4 Modularity in use

Modularity in use is a consumer driven decomposition of a product with a view to satisfying the ease of use and individuality (PANDREMENOS et al., 2009). The authors also mention that the latter is intimately connected to the concept of mass customization. This modularity approach is strongly linked with modularity in design (product architecture), since it allows different component combinations to provide variety to attend customers’ needs and expectations with agility and quickness (SAKO; MURRAY, 2000; CARDOSO; KISTMANN, 2008).

4. Modularity in the automotive industry – concepts, benefits and difficulties

Modularity is present in a variety of industries, such as electronic components (as cameras or computers) and especially the automotive sector have been applying the modular strategy in its products and processes (ARNHEITER; HARREN, 2006; SALERNO et al., 2009). It is clear that with the automotive sector high growth and consequently increase in production and consumption of vehicles in Brazil and worldwide, the competition among OEMs has increased considerably, which generates a crescent need for competitive advantages and attractive requirements to customers and consumers. According to Pandremenos et al. (2009), automotive OEMs usually consider modules as a collection of components, physically close to each other that are both assembled and tested outer facilities and can be assembled very basically onto the vehicle.

In the automotive sector, Baldwin and Clark (2000) and Morris and Donnelly (2006) say that there are usually two modularity approaches: product modularity and production modularity. In other words, Pandremenos et al. (2009) classify two types of modularity in the sector:

- Level-1 or assembly modules, which is the practice of shifting sub-assembly lines that manufacture modules next to the final vehicle assembly line to separate supplier facilities at some distance from the plant and no radical change in the design of the module is affected; and
- Level-2 or design modules, which are modules that are optimized at the final assembly level by independent suppliers.

However, another modularity approach has been used in the sector: the modularity in use, which considers the customer's needs and customization characteristics regarding the product (CARDOSO; KISTMANN, 2008; PANDREMENOS et al., 2009). This latter modularity approach is used to add value to final product, as a way to satisfy customers' needs, since the production modularity objective is to improve production performance and efficiency, but not always complying with consumers' requirements (CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011).

According to a number of authors, modularity brings the following benefits:

- Complexity reduction of product specifications and activities (POLITZE; DIERSSEN; WEGENER, 2012; CHRISTENSEN, 2011; CAUCHICK MIGUEL; CABRAL NETTO; MARIOKA, 2009), by specifications' partition through the product developed modules. It facilitates comprehension about the product architecture, turning specifications more simple and enlightening;
- Product development time reduction (ZIRPOLI; BECKER, 2011a, b; CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011; JACOBS; VICKERY; DROGE, 2007), which optimizes lead-time and contributes to the application of concurrent engineering principles;
- More specialized suppliers (ZIRPOLI; BECKER, 2011b; MONDRAGON et al., 2009), since the division of modules force suppliers specialize themselves to provide the best solution in their components, potentially facilitating innovation and competitive advantages for both suppliers and OEMs (Original Equipment Manufacturers); and
- Suppliers in a higher level of maturity regarding modularity have more potential to add value for the OEMs and their business, through constant creation of competitive advantage, contribution and commitment for product customization (PRIETO; CAUCHICK MIGUEL, 2011). This benefit can also

enable long-term contracts and a closer relationship between OEMs and suppliers.

However, modularity also brings some disadvantages and difficulties:

- Loss of control in product development activities by the OEMs (ZIRPOLI; BECKER, 2011a, b), since the responsibility transfer to suppliers make them more autonomous. Carnevalli, Varandas Júnior and Cauchick Miguel (2011) corroborate that argument by saying that suppliers make more decisions about product design because they become the main modules' responsible;
- Increased supplier dependence by OEMs (RODRIGUES; CARNEVALLI; CAUCHICK MIGUEL, 2012; ZIRPOLI; BECKER, 2011a, b; CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011): this dependence can bring problems in OEMs' organizational and production processes, which can affect the OEM/suppliers relationship. In addition, many defined specification will only be observed and tested after assembling the components, which can generate high costs (even recalls, depending on the case) in case of non compliance and/or inconsistency in the complete assembled product; and
- The same dependence related above, but in reverse: suppliers can become overly dependent on automakers, which can have complete design control (CERRA; MAIA; ALVES FILHO, 2011; MELLO; MARX, 2007). Besides, OEMs can define the supply participation degree on projects (SALERNO et al., 2009). This action can generate considerable restrictions and minimal influence on modules development by the suppliers, complicating the search for components innovation.

Literature on modularity describes different approaches within the world. For example, Pandremenos et al. (2009) and Carnevalli, Varandas Júnior and Cauchick Miguel (2011) say that in Western and Japanese auto industries have been following dissimilar ways in implementing modularity: the latter has preferred the adoption of modularity in design, while the first considers more modularity in production. Hence, these differences might contribute with the lack of consensus towards a unique modularity concept. In the following section, a literature summary on modularity is presented.

5. Literature summary on modularity

After examining studies regarding modularity and its various domains (such as modularity in design, production and use), it is possible to point out some recommendations and features for the adoption of modularity according to the literature. Firstly, modular products manufacturers

may develop stronger communication among module development teams (LAU; YAM; TANG, 2011), aiming to improve definition of responsibilities as well as the relationship between companies. In this sense, there is an additional need of efforts towards a better coordination and management of modular components (MIKKOLA, 2007), since this additional endeavor might contribute in minimizing tolerance management issues, maintaining components standardized (PANDREMENOS et al., 2009).

Regarding production modularity, the means of modularization on the factory floor is the ability to pre-combine a large number of components into modules and these modules to be assembled off-line and then brought onto the main assembly line to be incorporated into a small and simple series of tasks (SAKO; MURRAY, 1999). Paralikas et al. (2011) argue that agility is necessary to product all available modular product variants quickly, to better attend consumers' needs and expectations and lower costs to enable it, simultaneously.

Nevertheless, although literature affirms that there is not a consensus (for example in GERSHENSON; PRASAD; ZHANG, 2003), it seems to have an agreement regarding modularity: every system is modular to some extent; very few systems are composed of parts that interact and affect each other so tightly that there is no opportunity to mix-and-match the subsystems they are made of (CAMPAGNOLO; CAMUFFO, 2010). Mello and Marx (2007) study corroborates, stating that rarely a product is only integral or modular; a product is classified in relation to other products according to its modularity degree. The next section will point out the main conclusions regarding this study.

6. Conclusions

This paper aimed to systematically examine studies about modularity and its applications in the industrial and organizational context, dealing with different modularity facets. The interest on modularity is becoming ascendant. Perhaps may not be necessary become within a generic and accepted definition to continue the evolution and comprehension of modularity theory. On the other hand if consolidated it can potentially affect it in a positive manner. Varieties of modularity stem from different applications of the concept and each application carry on a specific perspective. However, some terms have to be remembered when dealing with modularity, such as: "form", "function", "interchangeability", "independence" and "similarity". The module concept is well understood by the literature, although it has broad interpretations according to each approach (design, production, use, service and/or organizational). The different modularity domains are extremely connected among themselves and one of them, i.e. modularity in design, normally guide the others.

In this context, modularity in design, where functional perspective is more utilized, is the most prominent approach, followed by production modularity, where the division of physical component is priority in order to reduce operational costs and support better production line, and modularity in use, which addresses customization features in order to meet customer expectations. Besides these three approaches, studies have been conducted on service modularity, aiming to organize elements and requirements of intangible processes in a modular way (grouping these characteristics "module-by-module"), and organizational modularity, which deals with the definitions towards managerial processes modularization to improve definitions in managerial activities and tasks among organizations or within a company itself. In addition, there is a trend to maintain the lack of consensus regarding a universal modularity concept due to different approaches used, as previously discussed. For example, modularity in design usually refers to product functionality, an aspect that is not essential if applied in production process as well as modularity in use may not be the best approach to managerial processes, and so on.

Further research should investigate a better understanding about variations of modularity concept, trying to find what characteristics are predominant throughout all concept variants (design, production, use, organizational, etc.). Another opportunity is to investigate variants of modularity concept as well as the influence of these variations among industrial sectors that often use the concept, such as automotive, electronics, furniture, etc.

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