An exploratory investigation on modularity adoption in design and production through a case-based research in a Brazilian automaker*

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Abstract: Many companies in the automotive supply chain have increasingly adopted the concept of modularity. Modularity can be defined as a way of building complex products or processes from smaller subsystems that can be designed independently and yet function together as a whole. There are many dimensions of modularity and the most common ones are: modularity-in-design and modularity-in-production. In addition, there are potential tradeoffs between these dimensions, but this issue has not yet been extensively explored in the literature. In this sense, the purpose of this paper is to empirically investigate to what extent the adoption of modularity varies according to such tradeoffs. Case-based research is employed as the methodological approach. The unit of analysis is a business unit of an international leading manufacturer of trucks and buses, being the latter within the scope of the present investigation. The findings describe various challenges and managerial implications that characterize various views on modularity with respect to design and production faced by the investigated organization. There is a clear distinction between the application of the concept of modularity in design and in production. Potential gaps in the literature are also proposed for further research.

Keywords: modularity, automotive industry, product design, production, case study.

1. Introduction

In automotive supply chains, the decision to adopt integrated product architecture in new product development (NPD) is increasingly being replaced by a modular approach, which has a tremendous impact on the strategic decisions that a firm makes. Conceptually, modularity can be understood as a way of building a complex product or process from smaller subsystems that can be designed independently and yet function together as a whole (BALDWIN; CLARK, 1997). There are potential tradeoffs between modularity in NPD and in production, which influences how modular assembly is implemented, and this issue has not yet been extensively explored in the literature. The purpose of this paper is to empirically investigate to what extent the adoption of modularity varies according to such tradeoffs. This work is a part of an ongoing research project on modularity in the Brazilian automotive industrial sector, which has a significant managerial and technological importance for the country, especially in the recent history of design and production of trucks and bus chassis.

The paper is organized as follows. The next section, a theoretical foundation of the paper is presented. Then, the case study is described to reveal the operational practices of modularity (both with respect to NPD as well as production) in a Brazilian manufacturing assembly line. Next, managerial issues that may or may not be affected by the modular concept in the case company are discussed. Finally, we provide some insights about our findings with respect to research gaps in the literature.

2. Literature review

The theoretical background of this paper involves a literature review on modularity and specific literature on production and supply chain management (SCM). For instance, modularity it is often described in association with product design (ULRICH, 1995; BALDWIN; CLARK, 2000; MIKKOLA, 2006), production (STARR, 1965; FISHER; ITTNER, 1999; NOVAK; EPPINGER, 2001), process (SANCHEZ, 1999; SKÖLD; KARLSSON, 2007), and organization (SCHILLING; STEENSMA, 2001), which make the adoption of particular strategies to vary according to these perspectives. The literature on production and SCM includes managing the global supply chain (SKJØTT-LARSEN et al., 2007; FIXSON, 2005; DORAN, 2003; MIKKOLA, 2003), mass customization (PINE, 1993; MIKKOLA; SKJØTT-LARSEN, 2004), and postponement strategies (PAGH; COOPER, 1998).

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2.1. Basis of modularity

The architecture of a product is the scheme based on which the functional elements of the product are arranged into physical blocks and how the blocks interact (HUANG, 2000). Product architecture can be categorized as integral or modular. Modular architecture is achieved by applying the concept of modularity (or modularization). It 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. There are a number of terms that are used to describe modularity, as shown in Table 1.

The literature usually groups the concept of modularity in the perspectives of design, production, and modularity in organization (SAKO; MURRAY, 2000; CAMUFFO, 2001; DORAN, 2003), and modularity-in-use (SAKO; MURRAY, 2000).

Modularity in design has been investigated to reduce design process complexity (ULRICH; EPPINGER, 1995; FUJITA, 2002). It can be 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). Product modularity and determination of modular configuration involve design evaluation, which can be performed from different points of view: function, flexibility, cost-effect, environment, technique, and complexity (BI; ZHANG, 2001).

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). It also refers to the organization of sub-assembly, pre-fitment testing of modules and transferring some of these activities to suppliers (DORAN, 2003). The influence of modularization on the factory shop floor lies in the ability to pre-combine a large number of components into modules, for these modules to be assembled off-line and then brought onto the main assembly line through simple series of tasks (SAKO; MURRAY, 2000).

Modularity in organization corresponds to the relationship of product architecture and organizational architecture (LANGLOIS, 1999; BALDWIN; CLARK, 2000; CAMUFFO, 2001). It is related to intra-firm and inter-firm organizational design (CAMUFFO, 2001), including governance structures and contracting procedures that are adopted or used to accommodate modular production in both intra- and inter-firm context (DORAN, 2003). Internal organizational design refers modular production in terms of designing manufacturing processes, and a significant consequence of this aspect of modularity is the cross-plant redundancy of work organization, logistics, and production equipment (CAMUFFO, 2001). Moreover, other authors (e.g. SALERNO, 2001) understand that modularity requires a special organization and managerial system linking suppliers and their customers.

Modularity-in-use is a fourth type found in the literature. It is a consumer driven decomposition of a product with a view to satisfying ease-of-use and individuality (SAKO; MURRAY, 2000). The authors add that there are several issues, which influence the consumer perspective on modularity: easy of use, ease of maintenance, and relative cost of different modules. Another aspect, which is also important, is compatibility. Examples are evident from the computer and automotive industries. IBM developed the modular computer in the 1960s because consumers demanded compatibility within a family of computers and across different generations of computers (SAKO; MURRAY, 2000). In the automotive sector, modularity-in-use is captured by the idea of customers buying products by mixing and matching elements to suit their individual needs and tastes, including 'modules' and 'options' (e.g. sun roofs).

2.2. Research issues on modularity

One of the potential gaps in the literature is the question of whether there is a relationship among the different perspectives of modularity (CAUCHICK MIGUEL, 2005), especially concerning design and production. The modularity perspectives are usually discussed separately in the literature. From the design perspective, product modularity is associated with organizational modularity (HOETKER, 2002). From the production perspective, modularity may goes beyond outsourcing, proximity or delivery of sub-assemblies (SALERNO; CAMARGO; LEMOS, 2008). Other issues are shown in Table 2.

3. Research methodological approach

The present work is exploratory, with the purpose to investigate current managerial practices that could be categorized within the perspectives of modularity mentioned above. The research question is concerned with the association between modular design concept and modularity in production and how those perspectives are seen by the companies, as identified in an earlier investigation (CAUCHICK MIGUEL, 2005). Case-based research (YIN, 1994) is applied as the research approach.

The studied company (name withheld for confidentiality reasons) was chosen due to its historical development of new products in Brazil. It is within the 50th Brazilian companies in terms of annual revenue and top five within the automotive sector. The annual revenue is about US$ 3.2 billion with approximately 11,000 employees. The company has a local development center responsible for truck and bus development for Africa, Latin America, and Middle East. Moreover, during the past years the company has consolidated the implementation of a local technological center for developing new products, with a work force of more than 500 people. In addition, it has design autonomy from the headquarters since the company is in charge of most of the engineering hours when developing new products for the abovementioned markets. Other criteria for unit selection was the accessibility to data that was facilitated through the collaboration of research projects carried out in the past with the company (CAUCHICK MIGUEL; SEGISMUNDO, 2006) as well as close contacts with a number of professionals working in the area of NPD. In this paper, the unit of analysis is the development of bus chassis. Although the company develops both truck and buses, the paper focuses on the bus chassis, as the company has almost full autonomy of its new development.

Table 1. Modularity Terms (MIKKOLA; GASSMANN, 2003 apud CAUCHICK MIGUEL, 2005).

Terms	References
Modular components	Sanchez and Mahoney (1996); Shaefer (1999)
Modular innovation	Henderson and Clark (1990); Christensen and Rosenbloom (1995); Hsuan (1999)
Modular product architecture	Ulrich and Eppinger (1995); Sanchez and Mahoney (1996); Lundquist, Sundgren and Trygg (1996)
Modular system	Langlois and Robertson (1992); Baldwin and Clark (1997)

Empirical evidence was collected from various sources: semi-structured interviews with middle managers and engineers in addition to site visits and archival documents provided by the company. This includes primary and secondary data. In the first preliminary data collection, middle managers presented an overview of NPD processes and modularity applications in two business units (truck development and bus chassis development), followed by a non-structured interview. Then, data on design as well as assembly were gathered during the second interview, from which the semi-structured interview was tape-recorded. The aim was to identify organizational practices that were triggered by modularity adoption. Typical interviews lasted two hours; they were transcribed and sent to interviewees for data confirmation and confidentiality checking. Additionally, on-site visits took place to observe modularity in the assembly as well as in product engineering (such as the testing of prototypes in experimental engineering). Further data was gathered through a sixteen-page questionnaire on 'modularity adoption in the automotive sector'. The questionnaire is part of a larger on-going descriptive survey-based research project on modularity in the Brazilian automotive industry. Although the questionnaire

Table 2. Issues of research on modularity (adapted from CAUCHICK MIGUEL, 2005).

Research focus	Potential general topics for investigation
Design	• cost and performance tradeoffs in modular product design
	• module size and boundaries definition
	• knowledge management in modular product design
	• collaborative design of modular product design
	• impact of modular design on manufacturing process and systems
	• contribution of modular design in organizational processes
	• modular development decisions in conceptual design phase
	• the relation between of modularity and degree of innovation
	• (re)organization structure for modular product development
Production	• lead time measured from when components are ordered
	• impact of variety/commonality of components for production
	• efficiency in manufacturing due to modular product design
	• production configuration due to modular decision
	• complex and ergonomically difficult tasks in modular production
	• changes in quality assurance and control due to a modular production
	• challenges in production management due to modularity
Organizational	• service operation complexity due to modular product design
	• warranty costs due to modular product design
	• new investments in plants, and merger and acquisitions
	• buyer-supplier relationships within a modular concept
	• outsourcing decisions when adopting modular product design
	• strategic flexibility through modularity in organization design
	• choice of suppliers based on their modular technical capabilities

encompasses a wider scope, it was important to analyze the industry in the context of modular concept as well as to triangulate evidence from the interviews, documents, and site visits. For instance, a relevant argument is that 'the company areas define their own concept of modularity', which was identified in at least three means of data sources. All sources were then reviewed and analyzed in order to identify and validate the theoretical construct.

4. Findings of a case study in a Brazilian bus manufacturer

The company adopted the concept of modularity ten years ago, mostly in design and production. The main drivers behind the introduction of the modular concept was to reduce product complexity (VELOSO; FIXSON, 2001), resources for developing the product (DORAN et al., 2007; ARNHEITER; HARREN, 2005), development cycle time (SANCHEZ; COLLINS, 2001; VELOSO; FIXSON, 2001), increase product variety (ORSATO; WELLS, 2007; SANCHEZ; COLLINS, 2001), and production flexibility (LAU; YAM; TANG, 2007; SANCHEZ; COLLINS, 2001). Other benefits are associated with the suppliers, such as to improve supplier conformity (ARNHEITER; HARREN, 2005), enable the supplier involvement in the assembler production (HOEK; WEKEN, 1998), and increase partnership between the assembler and suppliers in the development of new products (SILVA; ROZENFELD, 2007). The management of modularity in design and production are described below.

4.1. Modularity in design

NPD process was created in the company's headquarters and is based on ten stages and gates, similar to Cooper's stage-gate framework. However, additional requirements for APQP (Advanced Product Quality Planning) are also considered. Typical NPD tasks include the development of platforms (especially for new bus chassis) and derivative projects. The development of bus chassis comprises the definition of technical specifications, market needs, and legal requirements.

Bus customers include the passengers (i.e. users), the bus companies, and the 'body builders'. The last type of customer is relevant and more specific for developing countries. In Europe, for instance, a bus design is not a chassis plus a body built, *a posterior,* but an integral bus designing the chassis and body in a unique architecture. The company has two families of chassis: intercity bus and city bus. Each family has a variety of configurations (SPINELLI; SIMÕES; GONÇALVES, 2002). For instance, one can choose the configuration of a bus from two or three axle chassis, powered by engines from 110 to 420 HP and load capacity ranging from 5 to 40 tons. It can also have different transmissions, low roof or double-deck bodies, distinct driver position heights, and so on. These variants lead to a wide range of products so that all customer requirements can be fulfilled.

Next, the assembly line has to cope with providing the number of varieties. Usually, four prototypes are considered along with the development of a new product. The first one is a mock-up prototype for assembly and component positioning verification. The second one is the first vehicle that uses the defined position of components and a frame with enough strength that already enables to perform some functional tests. The third prototype has the final chassis design approved by analysis of parts and modules testing, from which endurance test for structural durability check is performed. Finally, the purpose of the fourth prototype is to check the production requirements and documentation, which also enables the team to validate the initial production job (job number one).

4.1.1 Modular concept in design

The new products must respect the current and future legislations, not only in terms of emissions and noise but also in terms of maximum allowed axle loading. The former is defined by legislations such as Euro III or Euro IV, for example (these are European Union standards for vehicle emission with either diesel or gasoline fuels). The latter varies according to front or rear axle and third axle in different countries (e.g., Argentina, Brazil, Chile, Mexico, and Germany) or political regional areas (e.g., Mercosul or European Community). The impact of legislation demands the assemblers to apply technologies such as emission gas reduction (EGR) or selective catalytic reduction (SCR). This leads to an increase in thermal load that affects, for instance, the module of engine and other sub-systems that are, in fact, related to the power trains such as the cooling system. The cooling system must be more efficient considering the different variants of chassis assembly. Figure 1 shows an illustration of modular design of a cooling system.

The bus design considers a chassis and a number of sub-systems, such as suspension, transmission, brakes, cooling, and so on. The chassis is consisted of a frame with two longitudinal bars joined with transversal rods that provide rigidity and flexibility. This frame is the spine of the bus and other sub-systems (e.g., the power train) are aggregated into the frame. In terms of design, the concept of the systems may be modular or not. Since the development of such systems is time and resource consuming, the development team makes efforts to utilize existing sub-systems and modules as much as possible. The competence of local suppliers is also taken into consideration at this stage. After defining the product concept, the frame of the chassis is designed. As the design of the frame is dictated by the various sub-systems, this process takes places concurrently with the development of modules.

Both product families (intercity bus and city bus concepts) make use of a modular concept that is understood as follows. The modularity in terms of loosely-coupled modules can be observed with the intercity bus. It is consisted of 5 modules: module 1 is the 'driver position' (cockpit), module 2 is the 'front axle' (tie rods, torsion bars, air suspension, dampers, brakes, tires, etc.), module 3 is a 'connection module' (a 'link module' to connect module 1 and 2 to 4 and 5 in order to enable the transportation of the chassis to the body builders), module 4 is the rear axle (axle, suspension, brake systems, tires, etc.), and module 5 is the 'power train' (engine, transmission, clutches, and other components, such as the cooling system). The tubes, wires, leads, etc. are not considered parts of any module. The aim of having a modular design for the studied company is to optimize design solutions in terms of variety of configurations, such as combinations of different bus families, engines, transmissions, front and rear axles, driver and other peripheral part positions, and so on. Moreover, the company aims at having a better communization of parts and modules, as identified in various sources of evidence (interviews with people from NPD, questionnaires, and company internal documents). Interestingly, the modular concept is not applied only based on product architecture or functional association (FIXSON, 2005). In addition, the standardization of interfaces is restricted and usually limited to the vehicles of the same family. Although this is a strong enabler for achieving modularity (MORRIS; DONNELY; DONNELY, 2004), it is not fully applied (and understood) by the investigated company. The company's understanding is that the 'design is modular because we managed to communize components'. Other functional areas have a different understanding of the modular concept as outlined next.

This observation, that companies have different interpretations of modularity, is also supported by other industries. In their earlier investigation, particularly with the Danish toy company, LEGO, Hsuan and Hansen (2007) identified eight factors that influence the management of platforms: the platform is based on one or more architectures; it forms a meaningful part of a product or process; it includes relevant knowledge at the architectural level; it serves as a basis for long-term development work; it serves as a basis for short and medium-term continuous improvement; it is based on a partly modular structure (by adopting modular architectures); it specifies internal and external interfaces; and, it is specific about where to gain effects.

4.2. Modularity in production

As with any automotive production processes, increased flexibility, better quality, higher performance are also critical factors considered by the company. In order to maximize the output of these factors, the vehicle assembly line is divided into two main stages: preliminary and final assembly.

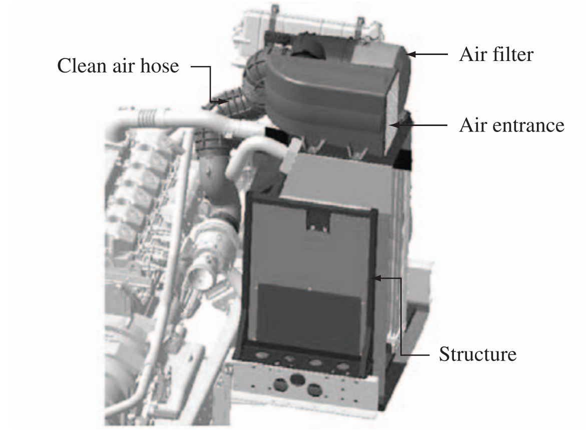

Figure 1. Example of a Cooling System (source: investigated company).

4.2.1 Modular concept in production

The preliminary assembly is the stage where all products have to pass through in order to a common 'base module' (i.e. a 'bus frame') to be assembled. It is a pull production system, facilitated by a suitable lay out with lean manufacturing principles.

The concept of supplying systems or components (and respective interpretation of modularity) in the assembly line is viewed in different perspectives: pre-assembly and final assembly. At the pre-assembly stage, modules are assembled into a unique set (e.g., a '*podest*' module). Interestingly, the company considers that a module is not related to a function in the vehicle, hence the term 'module' is only used at the preliminary assembly, as illustrated in Figure 2.

In the final assembly, two other concepts are used: system as a set of components or a sub-system with a defined function in the vehicle (e.g., cooling system, air reservoir, etc.) and a kit, which is a set of disassembled or partially assembled parts with or without fixtures. For instance, the kit for the rear suspension (i.e. springs, clamps, rods, etc.) can be assembled in the final assembly or pre-assembled. The components can be supplied together and disassembled or be pre-assembled as a rear suspension prior to final assembly and then assembled.

It is at the final assembly stage that the product differentiation takes place, where product variety and customization are obtained through mixing-and-matching of components. It is also a pull production system, applying the concepts of lean manufacturing. Here is when the sub-systems are supplied to the assembly line. The concept of pre-assembly is used to decouple assembly activities in order to supply the sub-systems in parallel to the assembly

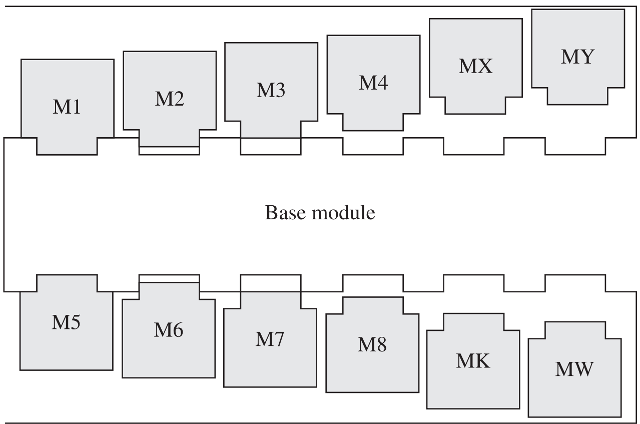

Figure 2. Modular Concept in the Preliminary Assembly (source: adapted from company internal documents).

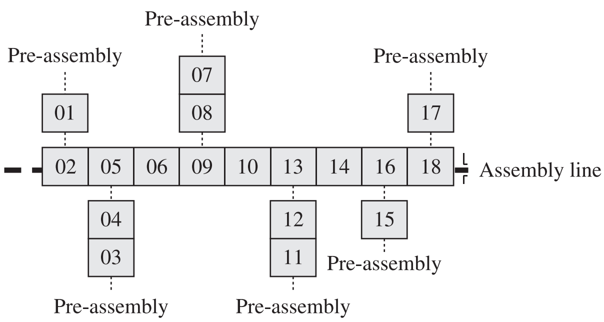

Figure 3. Modular Assembly (source: adapted from company internal documents).

line, similar as defined by Fredriksson (2006). However, the present study does not deal with the relationship between production modularity and coordination.

A closer look at the company's internal documents, it was noticed that the concepts of production modularity are articulated in the following way:

- Modular product: a vehicle with a modular design concept where systems and sub-systems are grouped by independent modules. They are dependent only in the final assembly. This concept is similar as the one in the literature (e.g., in BALDWIN; CLARK, 2000): 'building a complex product from smaller sub-systems that can be designed independently yet function together as a whole', i.e. when is finally assembled.
- Modular assembly: a process in the production when the main assembly line is conducted based on a base module (i.e. a frame) in which independent modules are assembled into the frame; the modules are pre-assembled off-line (as illustrated in Figure 3). This concept is in line with Sako and Murray's (2000) perspective except that in our case, the modules are incorporated into the frame concurrently, not as: "[…] through a small and simple series of tasks" (SAKO; MURRAY, 2000, p. 4).
- Module modular: it is an extension of the 'modular product' to the module. They are considered as independent and standardized sub-modules with inter-dependence in the final assembly line.

5. Conclusions

Surprising to the expectations of this investigation, the case study revealed that there is a distinction between the application of the concept of modularity in design and in production. The design modularity focuses on achieving a better communization of parts, whereas in the production modularity, the physical proximity of modules (in relation to the final assembly line) is a more important factor than their respective functional aspects.

Another issue of modularity that deserves attention is concerned with quality assurance. Error proof practices, such as *poka yoke*, take place in the pre-assembly stage of the module, of which the suppliers (internal as well as external) have the full responsibility. Quality control check points are only performed when the modules are being assembled into the main assembly line, thus non-conformities to specification are only discovered during this process. Depending on the seriousness of the non-conformity, rework is performed before the module is assembled into the final assembly.

Furthermore, the design of bus chassis requires a partnership between the chassis manufacturer and the body builders. The quality, specifications, and reliability of final product depend on the integration of those players. One of the main enablers to achieve this integration is the definition of chassis interfaces vis-à-vis the body structure of body builders. This is assisted by a finite element model analysis from the body structure provided by the body manufacturer in addition to a digital mock-up. The integration of NPD through adoption of modularity with respect to supplier-buyer partnerships is in accordance with the literature.

The way that the production is organized points out difficulties in understanding the tradeoffs between the concepts of modular design to production. Actually, the management of modularity in design and production is much more complex than suggested by the literature. The literature treats each of these notions independently of each other, without addressing potential tradeoffs and dilemmas.

Modularity works when the components or processes are decoupled, hence the stage gate approach to modularity in NPD seems to be applicable. However, when other dimensions get added (aggregated) to the process, the interface requirements become blurred (even when the processes themselves remain modular). For instance, the NPD process (with the 10 stages) and the production (pre-assembly and final assembly) can be considered as two independent processes (with embedded processes), of which the degree of modularity can vary. The complexity of the processes increases as the number of stages and respective embedded modules increase. The combinatorial properties of modularity would indicate that the combined output of NPD modularity and pre-assembly modularity (which becomes the input to the final assembly modularity) would make the production system extremely challenging to manage.

Although the gap between theory and practice is narrowing, there is still much room for improvement. From the case study presented and our previous work on modularity, we conclude that the following areas have not been quite fully addressed in the literature, such as:

- The impact stage gate process in the design of modular organizations
- Differentiation of the modularity concepts with respect to different functions and tasks performed in the context of supply chain
- The impact of total quality management principles on modularity and vice-versa
- The modularity strategy when it is seen from a systemic perspective (e.g., modularity gained from decomposition) or from operational perspective (e.g., modularity gained from aggregation of decoupled components)

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7. References

ARNHEITER, E. D.; HARREN, H. A typology to unleash the potential of modularity. **Journal of Manufacturing Technology Management**, v. 16, n. 7, p. 699-711, 2005.

BALDWIN, C. Y.; CLARK, K. B. Managing in an Age of Modularity. **Harvard Business Review**, p. 84-93, 1997.

BALDWIN, C. Y.; CLARK, K. B. **Design Rules – The Power of Modularity**. Cambridge, MA: The MIT Press, 2000.

BI, Z. M.; ZHANG, W. J. Modularity technology in manufacturing: taxonomy and issues. **The International Journal of Advanced Manufacturing Technology**, v. 18, n. 5, p. 381-390, 2001.

CAMUFFO, A. **Rolling out a world car: globalization, outsourcing and modularity in the auto industry**. Italy: Department of Business Economics and Management Ca' Foscari University of Venice, 2001. Available from: <http://www.imvp.mit.edu/papers/0001/camuffo1.pdf>.

CAUCHICK MIGUEL, P. A. Modularity in product development: a literature review towards a research agenda. **Product: Management and Development**, v. 3, n. 2, p. 165-174, 2005.

CAUCHICK MIGUEL, P. A.; SEGISMUNDO, A. An analysis of portfolio management in new product development: a case study in a truck company. **Product: Management and Development**, v. 4, n. 2, p. 87-94, 2006.

CHRISTENSEN, C. M.; ROSENBLOOM, R. S. Explaining the attacker's advantage: technological paradigms, organizational dynamics, and the value network. **Research Policy**, v. 24, p. 233-257, 1995.

DORAN, D. Supply chain implications for modularization. **International Journal of Operations & Production Management**, v. 23, n. 3, p. 316-326, 2003.

DORAN, D. et al. Supply chain modularization: cases from the French automobile industry. **International Journal of Production Economics**, v. 106, n. 1, p. 2-11, 2007.

FISHER, M.; ITTNER, C. D. The impact of product variety on automobile assembly operations: Empirical evidence and simulation analysis. **Management Science**, v. 45, n. 6, p. 771-786, 1999.

FIXSON, S. Product architecture assessment: a tool to link product, process, and supply chain design decisions. **Journal of Operations Management**, v. 23, p. 345-369, 2005.

FREDRIKSSON, P. Mechanisms and rationales for the coordination of a modular assembly system – the case of Volvo cars. **International Journal of Operations and Production Management**, v. 26, n. 4, p. 350-370, 2006.

FUJITA, K. Product variety o optimization under modular architecture. **Computer-Aided Design**, v. 34, n. 12, p. 953-965, 2002.

HENDERSON, R. M.; CLARK, K. B. Architectural innovation: the reconfiguration of existing product technologies and the failure of existing product technologies of established firms. **Administrative Science Quarterly**, v. 35, p. 9-30, 1990.

HOEK, R. I. V.; WEKEN, H. A. M. The impact of modular production on the dynamics of supply chains. **The International Journal of Logistics Management**, v. 9, n. 2, p. 35-50, 1998.

HOETKER, G. **Do modular products lead to modular organizations?** Urbana-Champaign: University of Illinois, 2002. Available from: <http://www. Business.uiuc.edu/ Working_Papers/papers/02-0130.pdf>.

HSUAN, J. Impacts of supplier-buyer relationship on modularization in new product development. **European Journal of Purchasing and Supply Management**, v. 5, n. 3/4, p. 197-209, 1999.

HSUAN, J.; HANSEN, P. K. Platform development: Implications for portfolio management. **Gestão e Produção**, v. 14, n. 3, p. 453-461, 2007. In portuguese.

HUANG, C. C.; KUSIAK, A. Modularity in design of products and systems. **Proceedings of the IEEE Transactions on Systems, Man., and Cybernetics, Part A**, v. 28, n. 1, p. 66-77, 1998.

HUANG, C.C. Overview of modular product development. **Proceedings of the National Science Council ROC (A)**, v. 24, n. 3, p. 149-165, 2000.

LANGLOIS, R. **Modularity in technology and organizations**. Research Papers Network Institutional Theory, University of Connecticut, 1999. Working Paper 1999-05.

LANGLOIS, R. N.; ROBERTSON, P. L. Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries. **Research Policy**, v. 21, p. 297-313, 1992.

LAU, A. K. W.; YAM, R. C. M.; TANG, E. The impacts of product modularity on competitive capabilities and performance: An empirical study. **International Journal of Production Economics**, v. 105, n. 1, p. 1-20, 2007.

LUNDQUIST, M.; SUNDGREN, N.; TRYGG, L. Remodularization of a product line: adding complexity to project management. **Journal of Product Innovations and Management**, v. 13, p. 311-324, 1996.

MIKKOLA, J. H. Capturing the degree of modularity embedded in product architectures. **Journal of Product Innovation Management,** v. 23, p. 128-146, 2006.

MIKKOLA, J. H. Modularity, component outsourcing, and inter-firm learning. **R&D Management**, v. 33, n. 4, p. 439-454, 2003.

MIKKOLA, J. H.; SKJØTT-LARSEN, T. Mass customization, postponement, and modularization strategies in shaping supply chains. **Production Planning & Control**, v. 15, n. 4, p. 352-361, 2004. Special issue on mass customization.

MORRIS, D.; DONNELY, T.; DONNELY, T. Supplier Parks in the Automotive Industry. **Supply Chain: An International Journal**, v. 9, n. 2, p. 129-133, 2004.

NOVAK, S.; EPPINGER, S. D. Sourcing by design: product complexity and supply chain. **Management Science**, v. 47, n. 1, p. 189-204, 2001.

ORSATO, R. J.; WELLS, P. U-turn: the rise and demise of the automobile industry. **Journal of Cleaner Production**, v. 15, n. 11-12, p. 994-1006, 2007.

PAGH, J. D.; COOPER, M. C. Supply chain postponement and speculation strategies: How to choose the right strategy. **Journal of Business Logistics**, v. 19, n. 2, p. 13-33, 1998.

PINE, J. **Mass customization, the new frontier in business competition**. Boston, MA: Harvard Business School Press, 1993.

SAKO, M.; MURRAY, F. **Modules in design, production, and use**: implications for the global automotive industry. Cambridge, MA: International Motor Vehicle Program - IMVP, 2000. Annual Sponsors Meeting.

SALERNO, M. S. The characteristics and the role of modularity in the automotive business. **International Journal of Automotive Technology Management**, v. 1, n. 1, p. 92-107, 2001.

SALERNO, M. S.; CAMARGO, O. S.; LEMOS, M. B. Modularity ten years after: an evaluation of the Brazilian experience. **International Journal of Automotive Technology and Management**, v. 8, n. 4, p. 373-381, 2008.

SANCHEZ, R. Modular architectures in the marketing process. **Journal of Marketing**, v. 63, Special Issue, p. 92-111, 1999.

SANCHEZ, R.; COLLINS, R. P. Competing - and learning - in modular markets. **Long Range Planning**, v. 34, n. 6, p. 645-667, 2001.

SANCHEZ, R.; MAHONEY, J. T. Modularity, flexibility, and knowledge management in product and organization design. **Strategic Management Journal**, v. 17, p. 63-76, 2006.

SCHILLING, M.; STEENSMA, H. K. The use of modular organizational forms: an industry-level analysis. **Academy of Management Journal**, v. 44, n. 6, p. 1149-1168, 2001.

SHAEFER, S. Product design partitions with complementary components. **Journal of Economic Behaviour & Organization**, v. 38, p. 311-330, 1999.

SILVA, S. L.; ROZENFELD, H. Model for mapping knowledge management in product development: a case study at a truck and bus manufacturer. **International Journal of Automotive Technology and Management**, v. 7, n. 23, p. 216-234, 2001.

SKJØTT-LARSEN, T. et al. **Managing the global supply chain**. 3rd ed. Copenhagen Business School Press, 2007.

SKÖLD, M.; KARLSSON, C. Multibranded platform development: a corporate strategy with multimanagerial challenges. **Journal of Product Innovation Management**, v. 24, p. 554-566, 2007.

SPINELLI, D. M.; SIMÕES, S.; GONÇALVES, A. A. Modular bus chassis development using modern simultaneous engineering tools. **Proceedings of the Society of Automotive Engineers – SAE**, 2002.

STARR, M. K. Modular production – A new concept. **Harvard Business Review**, p. 131-142, 1965.

ULRICH, K. T. The role of product architecture in the manufacturing firm. **Research Policy**, v. 24, p. 419-440, 1995.

ULRICH, K.; EPPINGER, S. D. **Product design and development**. New York: McGraw-Hill, 1995.

VELOSO, F.; FIXSON, S. Make-buy decisions in the auto industry: new perspectives on the role of the supplier as an innovator. **Technological Forecasting and Social Change**, v. 67, n. 2-3, p. 239-257, 2001.

YIN, R. K. **Case study research – design and methods.** London: Sage Publications, 1994. (Applied Social Research Methods Series).