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Use of product and production modularity in the automotive industry: a comparative analysis of vehicles developed with the involvement of Brazilian engineering centers

Adoção da modularidade em produto e em produção na indústria automotiva: uma análise comparativa em projetos de veículos com participação da engenharia brasileira

Fabrício Eduardo Henriques[1]
Paulo Augusto Cauchick Miguel[2]

Abstract: Modularity is a strategy adopted by many industrial sectors, either in product development or in industrial production configuration. In this sense, this paper investigates the key elements of modularity in design and production, seeking to formulate a proposal aimed to assess and compare the degree of modularity specifically in the context of the Brazilian automotive industry. The comparison was done considering vehicles developed with the participation of Brazilian engineering centre. Five key conceptual elements of modularity in design and four other elements of modular production were extracted from the literature and applied in the selected units of analysis. As a main result, we developed a categorization matrix for analyzing the modular degree of six vehicles. Fiat *Palio*'s design was considered as the highest degree of modularity in design and the GM plant at Gravataí (*Celta*) as the more typical modular organization within the studies vehicles and respective assemblers, based on the applied methodology.

Keywords: Modularity; Modular design; Modular production; Automotive industry.

Resumo: *A modularidade é uma estratégia adotada por diversos setores industriais, seja no desenvolvimento de produtos, seja na configuração produtiva industrial. Nesse contexto, o presente trabalho objetiva investigar os principais elementos da modularidade de projeto e de produção, tendo também como finalidade formular uma proposta para avaliação do grau de modularidade nessas duas categorias, especificamente no contexto da indústria automotiva brasileira, bem como aplicar a proposta a um conjunto de projetos com participação da engenharia brasileira. Para o desenvolvimento do presente trabalho, foram extraídos da literatura cinco elementos conceituais da modularidade de projeto e outros quatro relacionados à modularidade de produção, a serem analisados nos projetos selecionados. Como resultado principal, é apresentada uma matriz de classificação resultante da análise de seis projetos de automóveis desenvolvidos nos últimos anos, tendo como resultados o projeto do Palio com maior grau de modularidade de projeto e a planta da GM de Gravataí como o caso de maior modularidade de produção, segundo a proposta utilizada.*

Palavras-chave: *Modularidade; Modularidade de projeto; Modularidade de produção; Indústria automotiva.*

1 Introduction

Product architecture, also known as product structure, has been conceptually categorized in two types: integral or modular (Ulrich, 1995; Baldwin & Clark, 2000; Schilling, 2000). A product architecture is said to be integral when two functional elements are implemented using more than one block (or subsystem), or one block implements several functions (Jacobs et al., 2011). Moreover, the interaction among the blocks is not well defined. The authors mentioned above also add that the block is conceived aiming at achieving high performance and that barriers among the blocks are difficult to identify, if not non-existent. In an integral architecture, the change of a single component may require a new product design.

For modular architecture, the physical blocks implement one or few functional elements, their

[1] Programa de Pós-graduação em Engenharia de Produção, Universidade Federal de Santa Catarina – UFSC, Campus Universitário Trindade, CP 476, CEP 88040-900, Florianópolis, SC, Brazil, e-mail: fabricio_vp@hotmail.com

[2] Departamento de Engenharia de Produção e Sistemas, Universidade Federal de Santa Catarina – UFSC, Campus Universitário Trindade, CP 476, CEP 88040-900, Florianópolis, SC, Brazil, e-mail: paulo.cauchick@ufsc.br

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interactions are well defined, and it is generally crucial for the product's main functions (Jacobs et al., 2011). Addionally, also according to the previous cited authors, the change of a module during design can be performed independently, without the need to change other modules. The classic example for a modular architecture product is the personal computer, where the processor, the hard drive, the monitor, among other parts are developed and produced by different organizations and assembled by other companies (Baldwin & Clark, 1997).

According to the literature (e.g. Sako, 2003; Salerno et al., 2008), a passenger car may be considered an integral architecture product, considering that some car functions are spread across different parts of the vehicle. Salerno et al. (2008) reinforce that passenger cars are considered by many to be integral products and that they are not likely to be modular designs because some of the main functions and restrictions that production has to follow are holistic, such as the noise level and stability, which are not connected to a single part (or block/subsystem); therefore there is a difficulty in establishing criteria to evaluate the degree of modularity on a product such as a passenger car. On the other hand, Mello & Marx (2007b) state that the automobile may be understood as a modular architecture product if it is considered as a set of modules, components, and subsystems with specific defined functions (for instance, dashboard, engine, gearbox, etc.). Wang (2008), in turn, states that a passenger car can have a modular or an integral system, since some kinds of vehicles are more oriented to a modular system while others are oriented to an integral system. This also adds complexity when using this statement because there is no clear distinction of a modular system and an integral system yet.

Although there are different points of view among the publications, the modular approach may simplify the complexity of the assembly of cars, making it easier to share among different models, controlling in a fair way and obtaining gains in scale and scope (Morris & Donnelly, 2006). It is also possible to afirm that there is no simple way to quantify the degree of modularity built in a specific product. In fact, according to Ulrich & Eppinger (1995), a product cannot be classified as strictly modular or integral, but they can be categorized relatively to other products in accordance with its degree of modularity.

The types of modularity most covered in literature in automotive companies in Brazil are (Carnevalli et al., 2011, 2013): design modularity (or product modularity) and production modularity (or process modularity). Design modularity refers to the development a strategy for new products in which the interfaces among the shared components in a given product architecture are specified and standardized to enable greater possibility of components replacement among the product families (Mikkola & Gassmann, 2003). Production modularity enables the standardization and independent production of product's components before its final assembly (Baldwin & Clark, 1997).

The automotive industry has significantly contributed to the technological and managing advances since its beginning, and it is not different with regard to the adoption of modular strategy. The way the automobile sector glimpses these opportunities as a competitive differential indicates that the sector behaves as a trend indicator, which leads us to credit such deed to the consumers demand, besides intense and constant competition in this segment, which drives the vehicle companies to constant evolution, as already shown by other researchers (e.g. Ro et al., 2007; Salerno et al., 2009; Carnevalli et al., 2011, 2013).

In this context, this paper aims at investigating the main modularity elements by formulating a proposal for the assessment of modularity degree in design and in production within the automotive industry. The paper also compares the degree of modularity adoption (design and production) in automakers operating in Brazil. This comparison are carried out by evaluating passenger cars design with the participation of the Brazilian engineering centers from 2000 on as well as the production of such vehicles.

The paper is then structured in five sections, being the first one this introduction. Section 2 describes the research design and methodological procedures. Section 3 outlines the scenario where this phenomenon is investigated. Section 4 defines the modularity elements which are adopted as well as assesses selected vehicle designs and production based on a comparative matrix. Finally, section 5 draws the main concluding remarks of this study.

2 Research design and methodological procedures

This paper has two distinct phases: a theoretical and a conceptual one. The first one consists of a systematic literature review, which initially aims at presenting the main publications on "modularity in the automotive industry". This type of approach is highly important to establish the theoretical basis of a research (Lakatos & Marconi, 2006). The sources used to build the concepts were extracted from a constructivist structured process of literature review based on the work of Lacerda et al. (2011). The articles were obtained through relevant databases and selected through a filtering process. Major databases as Scopus (Emerald), ScienceDirect (Elsevier), Emerald Fulltext, ISI Web of Knowledge (Thomson Reuters) were used to search for the articles. These databases represent the main academic journals related to the subject.

Sixteen different combinations of key words were used to search (e.g, *modular design*, *modular production*, *modular adoption*, *automotive industry,* among others). The initial search resulted in a total of 705 articles. However, when reading the title, abstract and, when necessary, the full text, most of the publications discussed the subject "modularity" in a more general way. Thus, it did not offer conceptual aspects that could be adopted for further analysis. The publications were selected in order to include contents (in Brazil and abroad) that minimally discussed modularity within the scope of the Brazilian automotive industry. That corresponds to vehicle development that has occurred in the country as well as those which could contribute to identify the conceptual elements related to the modularity. This process resulted in approximately 50 publications, which were considered core to this study. Other publications were added afterwards by consulting academics and practitioners who collaborated by sending their work (e.g. Amatucci & Mariotto, 2012). More details of these references can be seen in Henriques (2013). EndNote® software was employed for managing the references in all phases.

In this first phase, the development of passenger cars in Brazil and their carmakers were identified considering a period of around one and a half decades. This period was adopted due to the increase in the amount of hours spent by the Brazilian engineering centers in the first stages of vehicle development, already highlighted in the literature (e.g. Cauchick Miguel, 2006; Salerno et al., 2008, 2009; Amatucci & Mariotto, 2012). As a main purpose, conceptual elements (constructs) were extracted from the publications of the two types of modularity most adopted in the country – design and production (for this argument refer to Carnevalli et al., 2013) – aiming to create an analytical table which enable the analysis of the adoption of these types of modularity of previous passenger cars developed in the country.

The second phase aimed at classifying the adoption of the two kinds of modularity (design and production) in in those vehicles. To do so, documents and reports with free access were retrieved from institutional websites (e.g. National Association of Automotive Vehicles Manufacturers or ANFAVEA and the National Union for the Industry of Components to Motor Vehicles or SINDIPEÇAS), doctorate thesis and master dissertations linked to the subject (e.g. Dias, 1998; Consoni, 2004), articles in peer-reviewed journals (main sources) e proceedings of national and international events (e.g. *Gerpisa International Colloquium*). Other data sources were also used as a secondary source, such as: automotive companies newsletters, marketing material from car companies (automakers and first tier suppliers), etc.

All articles were read in full, and content analysis was carried out. The content analysis consisted in a search by categories of the data (groups by similarities) in each one of the selected vehicle designs, from the sources previously described in order to identify relevant conceptual elements. The conceptual elements established in the first phase of the study were used. The analysis was considered as retrospective multiple cases (refer to Eisenhardt, 1989 and Yin, 1989), from which the obtained data analysis was predominantly qualitative (as established by Minayo et al., 2007). This aimed at enabling a categorization of the vehicles (the units of analysis) according to the degree of modularity in design and in production. Vehicle developed since 2000 with the participation of the Brazilian development teams are showed in Table 1.

Table 1. Development of new vehicles with the participation of Brazilian engineering.

Company/*Vehicle*	Year	Strategy[1]	References[2]	Level of competencies in NPD
Fiat/*Palio*	2000	D	[3,4,6-10,12,13,17,18]	Full derivative
GM/*Celta*	2000	D	[3,4,7,9,10,12,18,19]	Full derivative
GM/*Meriva*	2002	B	[1,2,4,7,8,10,12,14,18]	Partial derivative
Ford/*Ecosport*	2003	D	[4,7,10-12,18]	Partial derivative
VW/Fox	2003	B	[2,3,5,7-10,12-14,18]	Partial derivative
Renault/ Sandero	2007	D	[8,11,12,20]	n.a.
Peugeot/ Hoggar	2010	D	[11]	n.a.
Fiat/Novo Uno	2010	D	[16]	n.a.
GM/Trail Blazer	2011	C	[15]	n.a.

[1]For the strategy classification, the work of Sugiyama & Fujimoto (2000) were employed: (A) Design of a global product using a new platform (this category is not present in the classification in Table 1); (B) Design of a local product using a new platform; (C) Design of a global product using an existing platform; and (D) Design of a local product using an existing platform. [2]Sources: [1] Amatucci & Bernardes (2007), [2] Amatucci & Bernardes (2009), [3] Mello (2006), [4] Consoni & Quadros (2004), [5] Cardoso & Kistmann (2009), [6] Toledo et al. (2003), [7] Cauchick Miguel (2006), [8] Amatucci (2010), [9] Dias & Salerno (2009), [10] Salerno et al. (2009), [11] Ibusuki et al. (2012), [12] Quadros & Consoni (2009), [13] Carvalho (2002), [14] Amatucci & Bernardes (2008), [15] General Motors (2011), [16] Santo & Daxbacher (2010), [17] Dias (2003), [18] Consoni (2004), [19] Graziadio (2004), [20] Amatucci & Mariotto (2012). n.a.: not available.

From all developments with Brazilian engineering participation, the developments of Peugeot Hoggar, GM Trailblazer, and Fiat Novo Uno did not offer enough content (data) that could sustain an analysis regarding the types of modularity, as showed in Table 1. Therefore, they were not considered in the analysis.

3 Theoretical background on modularity

To enable the development of a classification on the adoption of modularity in each one of the types analyzed, the literature was reviewed searching for its conceptual elements and the existing relations among them in a modular system. Characteristics (i.e. conceptual elements) were then identified according to each type of modularity seeking to build a theoretical frame for further analysis.

Comparing the different ways in which modularity is defined and used in the publications, the definitions have been found to be similar at times, but not identical. To summarize how the term modularity is often used by researchers, it rapidly drives to notions of modules and interfaces. For some time now, some authors (Ulrich, 1995; Baldwin & Clark, 2000; Schilling, 2000) describe modularity as modules with relatively weak interdependence between each other and great interdependence on its own.

To cover these issues in a better way in order to elaborate the first analytical table, the basic principle applied to all types of modularity is clear (Jacobs et al., 2011): a hierarchically clustered system. It is possible to take from the systems engineering literature that a system is determined by its elements and relations among these elements (Maier & Rechtin, 2000). Similarly, every product can be described through its elements and the relation among them. From this view, two dimensions to describe a product's modularity can be defined: the elements of which the product is composed, that is, its modules, and the relation among those elements.

Modularity is a property of a set of products which can be called product system (Salvador, 2007). A product system can be a car model and its possible variants, commercialized in a certain time of the year or even something that was not produced yet. That is, it can be a sequence of vehicle designs and its variants to be produced in the future.

Regarding production modularity, Salerno et al. (2008) state that the change in the relationship between suppliers and manufacturers caused by modularity brings along an extension of the modularity concept for a service relationship between themselves, besides the division of investments and risks. Table 2 shows an adaptation of this definition for the modularity typologies analyzed, showing the concept of the modular system in product development, simplistically called product modular system and production modular system.

Modularity basically consists of the division of a product - or process - in modules composed of several tasks, stages, or even project activities - or components (Baldwin & Clark, 2000). Table 2 also shows that a product modular system can have several types of relations between the modules. These relations can determine or not a higher degree (level) of modularity.

Before presenting the relations that exist in these systems, their definition and criteria for classification, it is necessary to define the element that composes both systems. One of them encompass a great responsible for the intense and complex relations that define the modularity degree: the module.

3.1 Module definition

The essence of the division of a product in physical modules is well described in Simon's parable (Simon, 1962, p. 15) about the watchmakers:

> There were two watchmakers, one called "*Tempus*" and the other one "*Hora*"; they made fine watches and each one of them consisted of 1000 parts. *Tempus* built his watch in a way that if he stopped for a moment to answer the phone, for example, his watch would immediately fall into pieces and he had to start to assemble the elements all over again. The watches made by *Hora* were not less

Table 2. Definitions of modular design and production modular systems.

	Division	Composition of modules	Modularity degree
Modular design/product system (functional standpoint)	Product in modules	Characteristics or functions, defined in the product development	Defined through the relations between the modules and amount of functions
Modular production system (physical standpoint)	Process in modules	Manufacturing and/or assembly of components and/or physical subsets	Defined through the relations between the suppliers and the manufacturers

Source: Developed by the authors based on Maier & Rechtin (2000), Salvador (2007), Salerno et al. (2008), Jacobs et al. (2011).

> complex than the ones made by *Tempus*. However, he had designed his watch so that he could gather stable subsets of 10 elements each. Therefore, when *Hora* had to put the partially assembled watch on the counter to answer the phone, he would lose only a small part of his job, and his watch could be assembled in only one fraction of the time spent by *Tempus* to assemble his.

To define a module from the design modularity standpoint, it is necessary to decompose the product in subunits. The main modules presented in the literature related to the automotive industry are presented on Table 3. These modules form some kind of 'frame' of a product structure (similar to the one *Hora* made).

As can be seen, Table 3 shows several modules found out in the literature. It is also important to highlight that some are commonly found in several publications, while others are more common in a certain segment of the vehicles, such as the sunroof system, reported as a specific module for the segment of premium (luxury) cars and practically non-existent in simpler (popular) cars. In addition, there are modules that are considered submodules of a more comprehensive module, which is the case of the cooling system module, regarded to be sometimes part of the frontal module of the vehicle; this fact may explain the division of a modules in several levels, as already highlighted by Fredriksson (2006) and Pandremenos et al. (2009).

The approach adopted in this paper considers the structure of a product as essentially fixed (having little difference between the particularities of each design or company) and that the product characteristics may vary within the functional limits of the elements that compose the modules. Thus, only pre-determined subunits (modules) of the product can be replaced. The replacement of a module with another requires that the latter have the same functional contribution to the product without compromising its main function. Moreover, the interface must assure interchangeability of the modules, which is discussed in the next section.

Henderson & Clark (1990) state that a component is a physical portion of the product that embodies one of the main concepts of the design and performs a well-defined function. There is no well-defined function between the modules and the components for the purpose of this paper. When the term component was found in other papers to refer to what the literature points out as a typical module of the automotive industry (see Table 2), this was understood as a module, except in specific publications where the separation of similarity between the modules and components was clearly described. There was a similar decision in the distinction of modules and systems. The authors of this paper chose not to discuss those differences because it is out of the scope of this work.

3.2 Relational elements of the modular systems

The existing relations in the modular systems define the rate of modularity adoption in a product. The elements to be analyzed are presented next.

3.2.1 Design modularity elements

Modularity in design aims at reducing the conception time through simultaneous performance of design activities of the modules that compose the product or process. Sanchez & Mahoney (1996) discussed the product design with modular architecture as being a strategy to coordinate the spread knowledge by the externalization of the product development. The previous cited authors proposed that the division and coordination of product development activities are better managed through the structured decomposition of the system in a successive set

Table 3. Typical modules available in the literature.

Brake systems	Door panel	Rear suspension
Bumpers	Front axle	Road wheels
Car body	Front end	Roof
Car carpet	Front suspension	Seats
Cooling system	Fuel tank	Steering system
Engines	Internal finishing	Sun roof
Electrical wires	Lightning system	Transmission
Exhausting system	Pedals	Tires
Dashboard	Rear axle	Window glasses
Doors	Rear end	Wheel column

Source: Developed by the author based on Hoek & Weken (1998), Dias & Salerno (1999), Salerno (2001), Fredriksson (2006), Mello (2006), Morris & Donnelly (2006), Mello & Marx (2007a), Pandremenos et al. (2009).

of subsystems, given a complex system, such as a automobile development project.

When all product development activities are centralized under the responsibility of a single manager, coordination is performed by following the hierarchy. However, when the activities are spread among different organizations – whether different areas of a company or different companies – the system becomes open, i.e. theoretically there would not be a centralizer entity controlling all activities performed by different organizations (Mello & Marx, 2007a) resulting in the risk of 'knowledge loss' (for more details see Zirpoli & Caputo, 2002). In this case, the product design must be thought in a way that there is a higher interdependence level between the components, where the interfaces among the different components are well specified and standardized, but defined by a strong company in the chain. Today the integrators of such activities (the managers of these projects) are most of the manufacturers teams, and the standardized interfaces are the ones that enable the parallel performance of product development activities and their control by those who master the interfaces. Table 4 shows the definition of the elements of design modularity.

Even without using the same nomenclature presented in Table 4, some of these relations among the modules have already been discussed by Morris & Donnelly (2006). The authors described that a 'pure' modular product architecture occurs when a module controls a function, the manufacturer controls the modules design and specifications of interfaces as well as the relation with each other. These descriptions can be associated to the division of the product structure, the independence, and 'substitutability', respectively. Salvador (2007) also proposed the definition of different modularity elements, mapping by publications on the subject, similar to Table 4. In this sense, Salvador's publication (Salvador, 2007) was the basis for the definition of these conceptual elements, and the distinction among them. In the present paper an adaptation was done. The application of that is presented further ahead. The way in which these conceptual elements relate to each other is illustrated in Figure 1.

Each design modularity element is defined by its relational characteristics to other modules. The designs analyzed in the paper are classified by the presence of those characteristics. The definition of each element, their characteristics and how they contribute to the classification of projects is described next. It is also necessary to reinforce that these conceptual elements were extracted from the literature and adaptations were made:

- **Compatibility:** The term "standardized interfaces" came to exist when IBM used specifications that enabled the use of different processors, equipment, memories, etc. in a computer family (Salvador, 2007). The interfaces are shared connections between the components and the interface specifications define the protocol for essential interactions among the components; the rate at which the interfaces are standardized and specified defines the compatibility level among the components (Mikkola & Gassmann, 2003). The cited authors also stated that standard components have well-defined and standardized interfaces; therefore, product architectures composed by standard components are modular.

The interface compatibility between the modules of a product was reported by Hsuan & Hansen (2007) as the core of the organization of a modular platform because it enables the substitution of modules in certain product architecture, Standardized interfaces determine when the outsourcing is a viable strategy. Figure 1 showed an example in which three modules (M1, M2 and M3) are totally compatible among themselves and a forth module (M4) is compatible with just module M3, i.e. where there is module M1 or M2, module M4 cannot be present, and vice-versa. It can then be affirmed that module M4 is not compatible with module M1 or module M2.

A deeper analysis of the compatibility of modules can be made through data that may reflect the connection easiness among them in an approach called 'plug and play'. It can be inferred that modules with standardized and appropriately specified interfaces will always be connected to others that have the same standardization requirements. This aspect of product modularity analysis is, in fact, one of the greatest difficulties in the development of this paper because a passenger car, as already mentioned, is not fully subject to modular architecture, which increases the difficulty in finding data that shows how strongly the modules are connected.

- **Independence:** The central idea of independence refers to the capability of a system to be 'broken', i.e. dismembered in smaller units, or modules. From this perspective, when splitting up a complex system it becomes easier to understand, conceive and produce that same system than if it had been conceived and produced as a whole (Salvador, 2007). Baldwin & Clark (1997) support that modularity results from the conception of a complex product or process from smaller subsystems, designed

Table 4. Conceptual elements (constructs) in design modularity.

Possible relations among the modules in product development	Meaning	References
Compatibility or interface standardization	Existence of compatible interfaces to 'bind' the modules, standardized interface	[2,3,6-8]
Substitutability or component combinality	Existence of different models of a single module, the combination of different modules results in variability for a model	[2,3,6-8]
Sharing or commonality	Interchangeability of modules between the product family	[2,7]
Independence (loose coupling)	A system that can be partitioned in smaller units (modules), and that can be designed independently	[3,4,6-8]
Product structure division (function binding)	Describes the product in terms of its functions, it is the mapping of functions for physical components	[7,8]

Source: [2] Gonzalez-Zugasti & Otto (2000), [3] Hsuan & Hansen (2007), [4] Fredriksson (2006), [6] Mikkola & Skjott-Larsen (2006), [7] Salvador (2007), [8] Mikkola & Gassmann (2003).

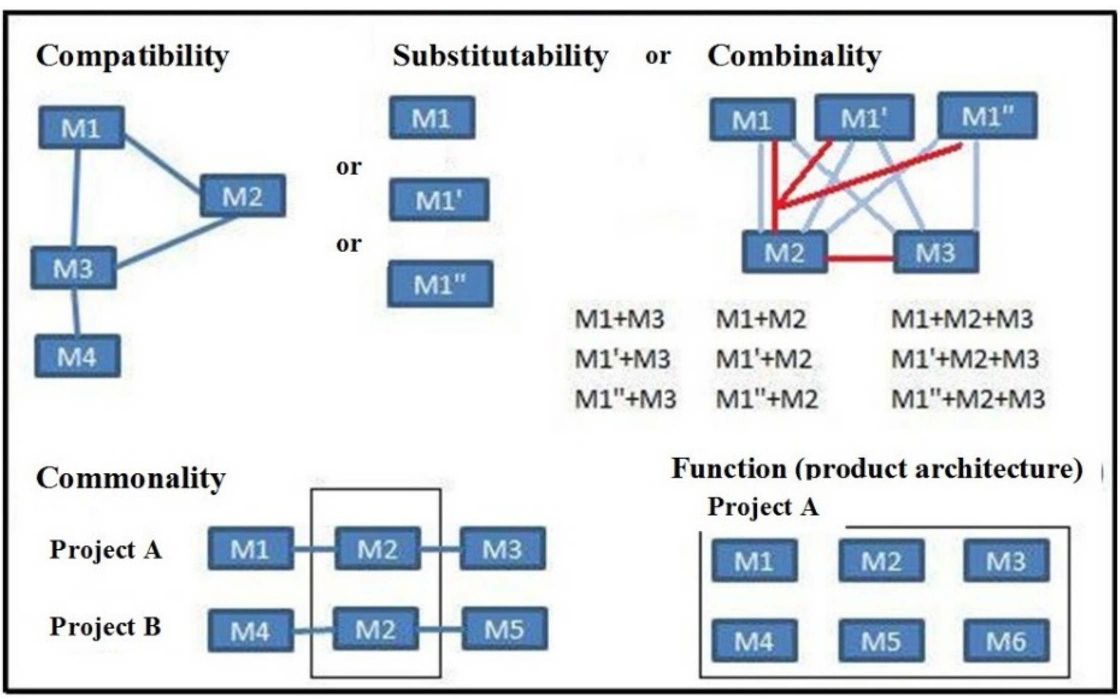

Figure 1. Relational aspects of the modules under the perspective of each design modularity element (graphic representation developed by the authors based on Salvador, 2007).

independently, which work in a set as a whole, being an efficient strategy to organize complex products and processes. Modularity intentionally creates a high level of independence among the components design though standardization of components interface specifications; therefore, modularity can move a company to a vertical disintegration (Langlois & Robertson, 1992; Baldwin & Clark, 2000; Mikkola & Gassmann, 2003). From the manufacturer standpoint, the more specified and independent a module is, the higher the chances of externalizing its development. This is not only a make or buy decision, but also a definition of the core competencies or maintenance of innovative capability by the manufacturer. However, from the point of view of this article, it was assumed that the externalization indicated greater signs of independence among the modules.

This conceptual element can be analyzed, then, by the existence of modules being developed by third parties, suppliers. In this way, the product is required to have very well drafted architecture so that the product can be divided appropriately, generating a high independence level among the modules and enabling them to be designed separately and even simultaneously.

- **Substitutability:** Products are modular when different product configurations can be obtained mixing and combining components from a certain set (Salvador, 2007). The essence of the components "combinality" vision - originated by Starr (1965) - is to maximize the combinatory assembly variety from a number of components based on a set of options. This perspective places the product modularity as a way to fulfill the fragmentation of market demands by increasing the range of options in a product line. The company must develop variations creating variants of the main product modules, leading it to different market segments.

An implication of this concept is that different market segments require slightly different products. The variants of the products directed to each segment must be distinct in one or more modules, and the remaning of the product must remain unaltered. Langlois & Robertson (1992) built the notion of modular system based on Starr's (1965) combinatory view, where they defined that a modular system can be seen as a product already defined in its final form, but that can be divided into subgroups of products that the customers can organize in several combinations, according to their personal preferences.

Figure 1 showed an example where module M1 has a high rate of "substitutability", and it can vary among the 3 available models. In a hypothetical situation where the product architecture forced the presence of at least a second module besides module M1, the product would have at least 9 types of possible configurations, the more possible configurations, the more modular it would be, because it would make batch customization easier and would be able to reach more market segments.

- **Commonality:** This concept is commonly expressed in previous studies (e.g. Ulrich & Tung, 1991), and expresses the existence of modules beyond the one that allows variety in a product, i.e., its use in different product lines or families. The cited authors proposed this notion as "components sharing modularity" or, as adopted in this paper, "module sharing among different products".

Figure 1 previously presented product architectures of two different products. Both designs A and B have 3 modules, but only module M2 is common to both designs. Shared modules in different projects enable manufacturing scale gains. In that way, this paper seeks to identify if the modules of a certain project are shared with the other products from a company and, in this sense, if they become more modular due to presenting gains in the production scale.

- **Division of the product structure in functions:** This element describes the product in terms of functions that it performs and how those functions are related; the definition of product functions structure is an essential step in the project engineering of the process (Salvador, 2007). According to Ulrich (1995), it is the mapping of functions for physical components where each module is responsible for assuming only one function.

Adopting the definition that a module performs a function that is well defined given the project's complexity of a vehicle and the difficulty in checking the amount of functions performed by the modules, in order to analyze that in the present paper, this element is considered by the quantity of existing modules. The example on Figure 1 showed a product with 6 modules regardless of their relationship that can be combined with or changed to other products etc., i.e. it is basically a list of exiting modules for that product; the more existing modules, the more modular it is.

For the purposes of this study, all five characteristics reported earlier were considered as having the same weight for the analysis of the modularity degree. For each one of these conceptual elements there is a qualitative attribution of three different levels "low", "moderate" and "high", considering only the conceptual element analyzed, regardless of the other ones.

3.2.2 Production modularity elements

When analyzing the new and complex relations between manufacturers and suppliers after the advent of the modular plants and aspects of coordination and flow of materials, it is possible to consider a higher modularity adoption degree. Thus, some aspects of production modularity is discussed next.

Arnheiter & Harren (2005) define the main production modularity elements as: "favoring to mass customization" and flexibility and integration with the supplier". Similarly, Fredriksson (2006) names "coordination" the integration with suppliers. Doran (2003) basically refers to typical relations established between large manufacturers in their network of hierarchically organized suppliers (differentiating the suppliers in tiers) through the transference of pre-assembly activities and module tests to suppliers.

Collins et al. (1997) describe a transitory evolution process of automotive plants configurations, going from *just in time* (which is an evolution of "*Fordism*") to a modular production, passing through the industrial condominiums and getting to the other extreme: the modular consortium. In a similar way, Pires (2001) adds the increase of activities outsourcing in this same path of transition among those configurations.

In summary, the main relationship aspects between automakers and suppliers identified in the literature can be considered:

- Productive arrangement configuration (Collins et al., 1997; Camuffo, 2000; Pires & Sacomano, 2010; Sako, 2006);
- Outsourcing of activities and integration with the supplier (Collins et al., 1997; Doran, 2003; Arnheiter & Harren, 2005; Fredriksson, 2006; Sako, 2006; Pires & Sacomano, 2010).

In the context of modular production, regarding the outsourcing of activities (such as modular assembly), the more externalized the activities are, the higher the modularity degree. Regarding the productive arrangement, the following types of relationship in a modular production are taken into account:

- **Assembly done directly on the assembly line by suppliers located in the plant (modular consortium):** a key example of full modular production is VW's truck plant in Resende (from a couple of year ago named *Man Latin America*), where most part of the responsibility for the production of the vehicles was outsourced to suppliers (Dias, 1998; Pires, 2001; Vasconcellos & Hemsley, 2002). In the modular consortium, the module assembly is done directly on the final assembly line, with labor from the suppliers themselves that work exclusively for the manufacturer (Pires, 2002).
- **Module delivered on the assembly line by suppliers located in the same land (industrial condominium):** according to Salerno (2001) and Pires & Sacomano (2010), in the industrial condominium the main suppliers in the first tier of the supply chain (also called 'systemists') are installed in the same groung as the assembler. The suppliers are not however responsible for the assembly rights of the final product, leaving such function to the assembler labor. In this situation, the location of the suppliers is tied to the manufacturer's logistics, being designed by the assembler and negotiated with the government when necessary. According to Dias & Salerno (1999), the industrial condominium can be defined by its configurations where some suppliers, chosen by the automaker, establish their facilities in the surroundings of the manufacturer's plant and start to provide components or complete subsets. The automaker is the leader of the whole project. That means that it is the assembler that decides which products will be provided through the condominium, which companies should supply those products, where they will be located in the condominium and how the deliveries should be made, besides the frequency of delivery, and technical specifications of the product, including price (Salerno, 2001).
- **Module delivered on the plant by suppliers located in a certain distance area (industrial district):** also known as industrial facilities (when the main suppliers are very close to the manufacturer), the industrial district is characterized by the dense concentration of suppliers and manufacturer in a certain region, which among other aspects, makes it different from an industrial condominium (Salerno, 2001). The suppliers are located not within the same land, but at a distance of some dozens of kilometers (Salerno, 2001; Sako & Murray, 1999), which enables the delivery of modules *just in time* according to the manufacturer's needs. However, the farther location affects the service provision, but, among other benefits, this configuration is associated to a greater proximity of facilities and the easier way of

exchanging information. Regarding the supply for subsystems, as the complexity of a product to be provided increases – i.e. a subsystem instead of a component – the need for an efficient technical assistance service increases, enabling the immediate solution of small problems in the assembly line, avoiding downtimes. In one hand, not sharing the same land does not mean that the suppliers are exclusively producing to the assembler. On the other hand, it does not allow the sharing of structure costs.

According to Dias & Salerno (1999), the installation of plants in an industrial district is up to the company, and that decision is made by an investment viability analysis, which can include analysis of the infrastructure conditions, qualification of labor, and easiness of obtaining raw material. Thus, any company can, in theory, install themselves in the district.

- **Components delivered on the plant, module preparation and assembly made by the manufacturer:** Similar to the conventional production, this type of relation is the simplest of all the ones presented because the manufacturer continues to perform and manage the whole production chain. That includes the assemble of the modules, which reach the manufacturer in separate components, and the suppliers are located in many different regions.

Salerno's (2001) point of view that the relationship among suppliers and the assembler in the industrial condominiums goes beyond the proximity, shows the need for other aspects to be assessed as well, besides the organization of production and outsourcing of activities. Additionally, Sako (2006) and Salerno (2001) include two other perspectives of analysis related to the production modularity that are also considered in the present paper in order to extend this analysis: the sharing or ownership of assets and the management of human resources.

The outsourcing deals with the redesign of the company's frontiers. However, the way the economy considers of outsourcing differs from the manner engineering sees it and the approach of managers. The economy defines outsourcing as the expropriation of assets. In this sense, there is a division of investments and risks, where the outsourcing of assets such as lands, plants, and equipment is considered by increasing the modularity degree (Sako, 2006).

Another factor that can influence the production modularity degree is the way the human resources are managed in each assembler. Sako (2006) proposes that this assessment should consider social relation standards with the suppliers and employees. Once these arrangements bring new ways of relationship between the assembler and suppliers, these two analysis dimensions appear, and that can increase the modularity degree of the analyzed system.

To sum up, the classification in production modularity gives importance to four factors: the type of arrangement (in strong evidence in the literature), the level of activities outsourcing, assets ownership and management of human resources. Differently from the five analysis elements in design modularity, the conceptual elements mentioned do not have the same weight for the analysis of the modularity degree. Given the importance verified in the literature regarding the type of manufacturing arrangement, it shall be considered that this element weighs twice the rest of the elements. Similar to the design modularity, each of these elements is classified qualitatively in three different levels: "low", "moderate" and "high", considering only the analyzed element, regardless of other elements in addition to the characteristics identified in each vehicles related to the others.

4 Analysis of vehicle developed in the country

The literature highlights the increasing participation of the Brazilian engineering sector in the development of new vehicles over the past decades. Rather than the common adaptations to the local market (still existent), some developments are today increasingly more complex (e.g. Consoni, 2004; Ibusuki et al., 2012; Amatucci & Mariotto, 2012). The so-called second wave of investments in the automotive industry in the 1990s brought about the installation of several new manufacturing facilities (Cauchick Miguel, 2006), update of the ones which already existed, in some situations using modular arrangements. That became, then, a scenario favorable to the analysis of the modularity adoption degree, both in product design and production, considering the context of the national automotive industry.

The projects selected for this analysis considered those with the participation of the Brazilian engineering. In addition it was taken into account those which had available data in the subject: Palio by Fiat, Celta and Meriva by General Motors, Ecosport by Ford, Fox by Volkswagen, and Sandero by Renault.

In relation to the autonomy of the module design, i.e. the involvement of suppliers in the product development, partnerships were realized, e.g. in the seat design (*Fox*, *Meriva*, *Palio*) and *cockpits* design (*Fox*, *Celta*). In the case of Renault *Sandero*, accessible data indicate that 80% of all components have some contribution from the suppliers (Renault, 2011). Nevertheless, there was insufficient data on 'how to' this occurred. In addition, there was no data available for Ford *Ecosport*. In the case of Fiat *Palio*, a higher supplier involvement was observed in the development of modules, and they also designed the cooling system and lighting, raising this case to a higher degree than the others, thus classifying Fiat *Palio* as "moderate" in this sense.

Because automakers offer certain differences of the products, some of the modules are exclusively targeted to a certain model, which is the case of the seating system for VW *Fox*, GM *Meriva* and the *cockpit* for GM *Celta* and GM *Meriva* as well. The last one also had an exclusive module of door panels. Concerning Ford *Ecosport*, the tank and the doors were exclusive for this vehicle. All the models share engines with other vehicles of each family and brand. They also share a significant quantity of modules and components with another derivative model of the brand and, most of the time, share the same platform. In addition to that, VW *Fox* shares its *cockpit* with VW *Gol* (4th generation) and Fiat *Palio* shares the exhaust system with Fiat *Uno*. A negative highlight occurs with GM *Meriva*, which, besides the exclusive modules already mentioned, has low communization of parts with other platforms (in the order of about 55%).

From the previous report, the characteristics of the vehicle designs presented several differences, both in quantity (number of functions) and other elements. From the 26 modules typically found in the automotive industry listed on Table 3, approximately 80% were reported by some publication on VW *Fox*, GM *Celta* and Ford *Ecosport*. That shows a high division of product architecture, while in the other vehicles that figure is around 50%.

To analyze the production modularity, the productive arrangement of the plants was the main association factor to the modularity degree adopted in each company. In this aspect, this is demonstrated by the way the supplier companies are installed in relation to the manufacturer that the Ford condominium is the one which gets closer to a modular consortium, with suppliers inside working in the same building as the automaker and with supplier's employees giving support on the assembly line. Similarly are Volkswagen and GM at the plant of Gravataí city, where GM *Celta* is produced. Renault's plant was classified as "moderate" and, similarly, Fiat's arrangement; below all the others is GM's arrangement in the plant in the city of São José dos Campos.

Generally, the outsourcing of tasks is organized very closely by the assemblers. The automakers do not reach a level of outsourcing of activities as high as VW in the plant of Resende, but the suppliers are located close to the assembler, share the structure costs (sometimes even rent expenditures), and manage part of the supplier chain (in the lower levels of the chain). A negative exception is GM, where *Meriva* is produced with a low level of outsourcing of activities.

When analyzing the asset ownership, GM at Gravataí has advantages over the other plants. With the suppliers affording the land costs, buildings and equipment, the savings in investment by the assembler is notorious with regard to the installation of this new manufacturing complex (savings of 2/3 according to non-official data, as highlighted by Salerno, 2001). In the other cases, the investment done by the assembler includes lands and buildings, when located on the same property, as in the case of the plant in São José dos Campos. When the models are changed, the manufacturer itself is the one that will afford the cost of new tools. In this analysis, a low asset ownership, e.g. of GM at Gravataí is better than the other cases (with a "moderate" asset ownership).

The categorization of all elements in modular design and in modular production is summarized in Table 5. It is worth emphasizing that each of the qualitative assessment ('low', 'moderate', etc.) was based on the content analysis of the publications. In addition, each of them associates a value in a scale (for example, for 'low' the value is 1). Each value derived from Table 5 was then used for constructing (and positioning) each vehicle in the matrix showed in Figure 2, discussed further ahead.

Figure 2 shows data of Table 5 in a different way. In another words, qualitative data presented on Table 5 were "transferred" to the matrix based on the Quality Function Deployment (QFD) principles by giving the scores 1, 2 or 4, according to the rating obtained in each item of Table 5. Where there was no available data of a certain vehicle in some of the modularity types (design or production) and each respective element, the score attributed was 0 (zero), which is the lowest score in a QFD scale. The matrix of Figure 2 enables, then, to visualize the positioning of each of the vehicles according to the degree of design and production modularity.

It is important to reinforce that the result showed in the matrix (Figure 2) is not an exact quantification of the vehicle, but a first attempt at positioning those in accordance with each type of modularity degree, considering the two main types adopted in the country (Carnevalli et al., 2013): design and production.

Table 5. Modularity degree of the elements analyzed in the selected vehicles.

Modularity elements Fox		Vehicles					
		Celta	**Meriva**	**Ecosport**	**Sandero**	**Palio**	
Design modularity	**Compatibility**	n/a	Moderate	n/a	n/a	n/a	High
	Independence	Low	Low	Low	n/a	Low	Moderate
	"Substitutability"	Moderate	Low	Low	Moderate	Moderate	Moderate
	"Commonality"	Moderate	Moderate	Low	Moderate	Moderate	Moderate
	Functions	Up to 19 modules	Up to 21 modules	Up to 13 modules	Up to 21 modules	Up to 12 modules	Up to 13 modules
Production modularity	**Type of arrangement**	Advanced industrial condominium	Industrial condominium with advances	Conventional	Advanced industrial condominium	Industrial condominium	Initial industrial condominium
	Outsourcing of activities	Moderate	Moderate	Low	Moderate	Moderate	Moderate
	Assets ownership	Moderate	Low	Moderate	Moderate	Moderate	Moderate
	HR management	n/a	Low	n/a	Moderate	n/a	n/a

Source: Developed by the authors based on the literature analysis.

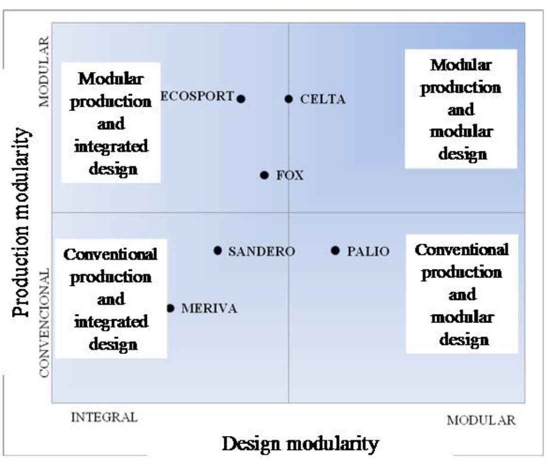

Figure 2. Classification matrix of the modularity degree.

4.1 Discussion

The asset ownership has generated an important discussion subject. The outsourcing of assets can be thought to reduce the manufacturer's management capability, which is one of the focus of modularity, i.e. in this aspect, the intention is to outsource in a way that the assembler can maintain some control and managing the processes, so can focus its attention in the customers or in new products that will come to the market.

With the outsourcing of assets, regardless of the division of investment risks, it is easy to realize a greater difficulty of managing the human resources in those companies, since the whole structure belongs to the supplier (see the GM Gravataí case). Another impairment that may occur is that in case when there is dissatisfaction caused by the service or product quality under supplier fault, in the business model in which the asset (land and plant) belongs to the assembler, it would be easier to negotiate with other partner if supplier replacement were needed. This fact has been identified in VW's truck plant in Resende (see Salerno, 2001 and Pires, 2002).

The oldest plants (for GM *Meriva* and Fiat *Palio*) were positioned at the bottom of the matrix (Figure 2), with the lower production modularity degree. This can be associated to the difficulty of adapting old plants to a modular arrangement, due to the difficulty in altering the layout and the working space to provide easier access to the suppliers.

In line with what some authors have already confirmed (see theoretical reference), the findings suggest (considering the sample of vehicles) that there is not a standard division of product architecture or modules. The statement that there could be a modular production without a modular design and vice-versa (Salerno et al., 2008) may be illustrated with the example of the engine module, a design that was done separately from the car development and that could be produced independently and assembled in the production line as well as in different vehicle models. The analysis in this paper can also indicate that that may really occur.

In fact, what the classification on the modularity adoption makes clear is that the GM *Celta* model is the most representative in terms of production modularity application in passenger cars within Brazilian engineering context. That occurs mainly due to the arrangement in the structure of an industrial condominium and by the high rate of assets outsourcing, being positioned ahead of Ford

Ecosport, VW *Fox*, Renault *Sandero*, Fiat *Palio* and GM *Meriva*.

In the other axis of the matrix (Figure 2), Fiat *Palio* represents the best of design modularity, mainly due to its high 'compatibility' among its modules. On the other hand, the vehicle design with the lower degree of design modularity was GM *Meriva*, which resulted in low 'independence', 'substitutability' and 'commonality'. A little ahead, from the lowest to the highest, there are Renault *Sandero*, Ford *Ecosport*, VW *Fox*, and GM *Celta*.

The only vehicle with the participation of national engineering that can be identified as the one with design modularity and production modularity is GM *Celta*. This vehicle was developed in parallel with the plant construction, which results in a remaining question: which type of modularity strongly influences each other (product or production)?. GM *Meriva*, where strong relation between the two types of modularity was not observed may be classified as an integrated design and conventional production as a much lower degree comparing to the other vehicles analyzed can be seen.

Modularity in production is a reality in Brazil for a quite long time. Since the implementation of the modular consortium at VW Resende plant, all the other assemblers have followed to some degree this kind of arrangement. A similar statement cannot be considered regarding design modularity. The passenger cars that can be considered with modular design are GM *Celta* and Fiat *Palio*, but both have been regarded as basic modular design, with a relatively low degree of modularity.

Differently from other studies which compare aspects of modularity in cars from the same manufacturer developed locally with cars developed globally, this study soughts to compare cars developed locally from different manufacturers. It is important to highlight that, obviously, there is a difference in the development of each vehicle due to different culture and strategies from each assemblers. Therefore, this may generate misrepresentation when assessing those different vehicles. Finally, the available and accessible data to perform this kind of analysis analysis are also a limitation in this research.

5 Conclusions

First of all, it is important to highlight that the paper has fulfilled its purpose of investigating the design and production modularity in vehicles developed in Brazil. In addition, it proposed an assessment of modularity degree considering these two categories of modularity. The comparison that results from the vehicles from different manufacturers has allowed seeing differences in the application of the types of modularity analyzed. It is also important to notice that the conclusive points derive from a scenario with the available data and do not allow generalizations for other projects, markets, and vehicles other than those covered here.

It has been found that there are differences in the vehicle projects concerning product and production modularity, when taking into account the conceptual elements selected in the literature. From the results, as expected production modularity is the one with highest adoption compared to design modularity. Nevertheless, in both modularity types when considering the analyzed projects are falling short of what could be considered a "state of the art". That can indicate more difficulty in the adoption of design modularity, hindering the expansion of modularity to beyond product assembly. It is also suggested that there is a gap of the evolution of the design modularity adoption in the product developments that occur in the country.

A limitation in the proposal refers to the scale adopted on matrix from Figure 2. Should another chosen scale be adopted, the vehicle projects could be positioned in other quadrants of the matrix, and that would alter the final position of some vehicles. Another aspect refers to the limitation of data collected in the field, which affected the assessment of the proposal. The data collection based on the literature on the subject restricts the analysis and some data was not available in publications or did not have enough details for the analysis. However, at this point, this may considered enough for this study.

Differently from other studies, which compare aspects of modularity in car designs of a single manufacturer developed locally with cars developed globally, this study aimed at comparing cars developed locally from different assemblers. Obviously, there is a natural difference in the performance of each vehicle design due to different cultures and strategies for each company (which was not covered in this study), both in relation to the design modularity and production modularity, which can generate bias in the assessment of each vehicle. That can be exemplified through the literature which state that the extension of outsourcing of activities depends on the strategies of each car assembler.

Finally, it is important to highlight that the present proposal needs to be further developed to include empirical analysis regarding the adoption of these conceptual elements. This is one of the future study to be carried out. herein addition, this proposal cannot taken into consideration the degree in which one conceptual element affects the other and this is something that remains to be further investigated. Another possible point to be investigated could be the barriers for the adoption of modularity, specifically the design modularity, which revealed a much lower level of adoption - than what was expected - than production modularity, maybe indicating more difficulty and complexity.

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