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Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry

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Abstract

Research in modularity design and in production systems in the automotive industry is increasing, as many Western and Japanese firms are applying this concept. This study focuses the relationships between modularity in design (MID) and production (MIP). After analysing 60 papers on MID and MIP in automotive companies, it was observed that some publications suggest that relationships between MID and MIP can be two-ways, i.e. not only the former affects the latter, but the latter also affects the former. Conclusively, the relationships between MID and MIP are relevant and future studies should emphasise how they produce managerial benefits and/or drawbacks.

Keywords: Modularity in design, Modularity in production, Cause and effect relationships

1. Introduction

The automotive industry is one of the most complex industries in terms of technology and agents involved in the innovation process. In order to reduce this complexity, modularity concept emerged, and has been widely used in the automotive sector. This concept was originated in the computer industry during the 1960s, generating competitive advantage and demonstrating significant importance in product development process (Arnheiter and Harren, 2006).

Within this context, a relevant issue was raised, which is the relationships between modularity in design (MID) and modularity in production (MIP) in the context of automotive industry. MID and MIP relationships have recently begun to attract scholars' attention, as many European, Japanese and North-American automotive firms are applying this concept to analyse how product and production modularity affect efficiency and competitiveness. Additionally, emerging economies like Brazil has been conducting more added-value product development activities in the past decades, which lead to some important changes within the automotive sector (Salerno et al., 2009), particularly from the modularity perspective.

Nevertheless, research about how MID might be connected to MIP (or vice-versa) is still scarce, even though some research have been pointing out the importance of this topic (e.g. Jacobs et al., 2011; Campagnolo and Camuffo, 2010). For instance, Brusoni and Prencipe (2001) argue that modularity in production and processes sometimes seems to be an inevitable result of higher degree of product modularity. On the other hand, Rodrigues et al. (2012) state in their study that modularity concept can be deployed in production without the product being necessarily designed in modules. Campagnolo and Camuffo (2009) state that it is not clear whether product modularity determines outsourcing or outsourcing activities and tasks affect product modularity.

From this scenario, the following research questions emerged: '*Does modularity in design leads to modularity in production (or vice-versa)?' 'Do such cause and effect relationship (if happens) bring practical benefits and/or drawbacks to automotive companies?'* Finally, *'What are the specific drivers and/or concepts behind these relationships and how can they enhance modularity's managerial benefits or generate drawbacks in the automotive companies?'*

This study analyses the possible relationships between modularity in design (MID) and modularity in production (MIP) theoretically. Moreover, it intends to verify if these cause and effect relationships bring managerial and strategic benefits as well as challenges for companies that adopt them. The argument developed in this paper culminates in a conceptualisation of modularity that considers an integration and existence of causal relationships between MID and MIP. In addition, this paper details how these relationships occur, through specific conceptual elements that lead these MID and MIP connections.

The remainder of the paper is structured as follows. Section 2 describes the research methods used to conduct this study. Section 3 shows the findings from this study. The paper finishes with a discussion of contributions in section 4, followed by conclusions, limitations, and further research opportunities (section 5).

2. Research Methods

The bibliographic search involved publications in peer-reviewed journals focused on the relationships between MID and MIP in databases such as Scopus, ISI Web of Science, Engineering Village (Compendex), Wiley Online Library, Blackwell, Emerald and Springer. The initial search, using the terms 'modularity', 'modular', 'modularization'/'modularisation' and 'automotive', yielded 307 papers. The search was refined after eliminating all papers that did not focus on modularity in design and modularity in production, since the interest is the relationships between these modularity typologies. The final selection included 60 references from the engineering and management literatures, mostly within the context of automotive industry. These papers focus most on the impact of MID and MIP in aspects such as company's performance, performance integration, supply chain integration, managing complex products, etc. Few papers focus specifically on the relationships between MID and MIP, which suggests an unexplored field of research.

Through a hypothetical-deductive method, based on Nunes and Bennett (2008), the focus was on building new conceptual evidence regarding the conceptual elements found in the literature on modularity and, through these concepts, establishing theoretical relationships between product and production modularity. Then, a theoretical framework is proposed regarding this relationship. Moreover, only MID and MIP was considered because these two approaches are the most exposed in literature, also mostly observed in the automotive industry in terms of practice and maturity degree. Conceptual elements of modularity were taken into consideration, since these concepts may be important to analyse the relationships between modularity typologies and to verify the feasibility of cause and effects relationships. Finally, it was investigated in what circumstances and how MID and MIP are linked and the possible implications in technical and organisational perspectives.

The choice for the automotive industry is due to its intense competition. Furthermore, modularity concept is relatively new in the automotive sector, introduced in the early 1990s. In this sense, there are still many challenges to overcome about modularity in the auto industry (Ro et al., 2007). Sanchez (2013) suggests that in spite of the effective strategic use of modularity by a few automotive firms, in the automotive industry generally there is still comparatively limited understanding of what modular strategies really mean and of the organisational changes necessary to implement modularity strategies effectively. Little is known about the implications of product architecture on organisational design both inside the company and the entire supply chain in the context of changes towards a more modular product architecture (Ro et al., 2007). In the next section, the findings of this study are presented. In addition, the analysis was narrowed down to give focus in the Brazilian automotive industry since it is one of the largest emerging markets in the world, responding in part to a call for more research on this region (Hoskisson et al., 2000). Besides, Brazil has the largest range of automobile brands being produced in a single country (Parente et al., 2011).

3. Findings

This section presents the specific conceptual elements involved in these relationships and a summary of the Brazilian automotive case regarding MID and MIP.

3.1. Conceptual elements involved in the relationships between MID and MIP

The first evidence found on causal relationships between MID and MIP is when MID leads to MIP. For example, Sanchez and Mahoney (1996) argue that modular product architecture can work as a 'leverage' for engineering outsourcing. However, the same authors, as Sako (2003) mentions, recognise that these relationships can be in both ways (this two-way trajectory will be discussed later). In another argument in this direction (MID to MIP), Brusoni and Prencipe (2001) affirm that modularity in production sometimes seems to be an inevitable result of higher product modularity degree.

Underpinning this causal relationship trajectory, Paralikas et al. (2011) say that product structure influences its production, since companies need to organise their production processes in an agile manner in order to provide all product variants developed. In addition, modular products can facilitate organisational redesign by companies (Hoetker, 2006), one of the influent aspects in modularity in production. Nevertheless, other authors argue that MIP might lead or affect MID, since in some cases manufacturing structure need to be taken into account before designing modular architecture. In this perspective, certain type of product architecture is restricted by the organisational capabilities of each company (Ro et al., 2007), i.e. it is necessary to evaluate all productive processes conditions and structure before establishing a redesign of a new modular product architecture. Changes in the hierarchies in production systems and/or inter-firm systems cause tension in their relationships with product architecture, and thus encourage the redefinition of product architecture (Takeishi and Fujimoto, 2003).

Although some authors argue that the relationship can be either from MID to MIP or vice versa, the literature shows more evidence demonstrating that relationships between MID and MIP can actually be a two-way trajectory, considering that both trajectories might occur. Takeishi and Fujimoto (2003) argue that the relationship between product architectures and inter-firm systems is two-way – not only the former influences the latter, but also the latter has some impact on the former. In addition, the trajectories of causal relationships between modularity typologies depends on the unit of analysis considered (Fixson and Park, 2008). Corroborating with this, Frigant and Talbot (2005) say that differences in the trajectories of adopting modularity are result of: (i) previous and current configuration of the industry in question; (ii) different product characteristics; and (iii) rate of technological change and organisational learning.

The following conceptual elements that influence on degrees of modularity in design and production can be identified: outsourcing, standardisation, commonality, functionality, product variety, interdependence between modules, co-design, and product platform development. Through the definitions of the conceptual elements, it is established here how MID and MIP are related to each other. Table 1 presents the most used and cited conceptual elements in the literature, followed by a brief description and the modularity typologies which they are commonly related.

Table 1 – Modularity's conceptual elements

Conceptual element	Description	References
Outsourcing	Consists of transferring assembly and/or engineering activities to suppliers. The level of outsourced modules/ components, as well as the level of influence suppliers have on the product development process, affect connections between MID and MIP.	Brusoni e Prencipe (2011); Ro et al. (2007); Mikkola (2003); Collins et al. (1997).
Standardization	Makes it possible to recombine the components of products without an elaborate adaptation of interfaces.	Jacobs et al. (2007); Brusoni and Prencipe (2001); Baldwin and Clark (1997).
Commonality	Refers to the level of modules/components that are common to different products. Sharing common parts contributes to MID and MIP relationships.	Pasche and Sköld (2012); Fixson (2007); Fisher et al. (1999).
Functionality	Refers to the ability or capacity of performing a task or function. Modules/components of a product may perform one or more functionalities according to the product design.	Sushandoyo and Magnusson (2012); Mikkola (2006); Baldwin and Clark (2000).
Product variety	Consists of offering a variety of products that the company makes available in the market. The bigger the variety, the higher is the possibility of offering product diversity.	Zeppini and Van der Bergh (2013); Liu et al. (2010); Pil and Holweg (2004).
Interdependence between modules	Refers to the degree of structural independence the modules/components have among themselves. The more independence they have, the more coupling and uncoupling autonomy and capacity the modules have, still being able to work together as a whole.	Zirpoli and Becker (2011); Baldwin e Clark (2000).
Co-design / Co-development with suppliers	Refers to the degree of suppliers' involvement in product development. Suppliers involved in earlier phases of the product development process tend to be more influent in the product architecture definitions.	Zirpoli and Becker (2011); Salerno et al. (2009); Campagnolo and Camuffo (2009); Ro et al. (2007).
Product platform	Consists of a central strategy for companies to handle agile manufacturing and new product development, which incorporate several approaches. Also can be a strategy to manage costs and variety in R&D and production.	Pasche and Sköld (2012); Hsuan and Hansen (2007); Sköld and Karlsson (2007).

Regarding outsourcing, Sako (2003) states that it can be made by: (i) designing modules and produce them in-house first, before outsourcing; (ii) outsourcing non-modular components before moving towards modular design; or (iii) simultaneously implementing modular design and outsourcing. Through these possibilities, one can observe that path 1 suggest modular design before considering modular production (through outsourcing modules and then more suppliers involvement) while path 2 suggest outsourcing before structuring product in modules. Lastly, path 3 seems to have the higher relationships between MID and MIP, since deals both with modular design together with outsourcing. In this context, Campagnolo and Camuffo (2009) argue that still it is not well defined if MID leads to outsourcing or if outsourcing of activities and components leads to product modularity. Apparently, both ways might occur, depending on each context and project developed.

Although it might be beneficial for OEMs and suppliers, some tradeoffs might occur when outsourcing. Zirpoli and Becker (2011) studied companies that faced problems in conducting outsourcing engineering tasks and activities, especially when trying to obtain higher product performance, since modular product design as an *ex ante* integration mechanism is not always effective for the integration of performances. Loss of learning by doing beyond the degree required to maintain component-specific knowledge represents a limit to design and engineering outsourcing (Zirpoli and Becker, 2011).

The application of the standardisation concept is established in the product development early stages, design specifications and the respective tolerances for each module . Thus, connections between product and production modularity through standardisation occur minimising variability in manufacturing processes, a key aspect of lean manufacturing that can be facilitated anticipating the inherent commonality of modular product architecture (Jacobs et al., 2007). Furthermore, MIP needs standardisation in order to favour process redesign and/or agile inclusion of new modules to meet product requirement changes (Mikkola, 2006).

Commonality is a concept more usual when studying products than processes, and explores the idea of using identical components in a one-per-product setting, but in different products (Fixson, 2007). This concept is characterised by grouping similar module variants to generate similar variations of a specific module type (Jiao et al., 2007; Watanabe and Ane, 2004). In this sense, specifications must be visibly defined to avoid inconsistencies connecting product modules and components. This suggests that commonality has also strong connection with standardisation of product interfaces, modules and components. However, in terms of product variety, commonality might bring some issues. For instance, Pasche and Sköld (2012) argue that the products become very similar with higher degrees of commonality among different products and/or brands.

Functionality is used to define how modules will be composed according to vehicle architecture and the functions of each module and subsystems that compose the vehicle as a whole. From this point, it is possible to build physically modular arrangement and their connections within the "systems" (see more in Ro et al., 2007), since modules and their couplings are organised towards manufacturing and assembly processes, considering limitations and potentials of the current productive arrangement. Manufacturing processes limitations are relevant because according to the product architecture, there might be the risk of the project to require high investment changes in the supply chain, which can inhibit the desired product conception.

Regarding product variety, Sanchez (2013) argues that the ready configurability of new product variations within a modular architecture substantially improves an organisation's ability to offer greater product variety. Modular architectures enable the creation of families of products in one development effort, not just single product designs. Product variety is a concept related to customisation level and it is usually defined during design phase in order to specify which components/parts will be able to customise and strategically selected according to customers' expectations (Stone et al., 2000). Through modular product architecture, it is possible to achieve products variants at low cost (Stone et al., 2000). Thus, seems that product variety is developed in the strategic objectives through modularity, prior to modular design activities, to then arrange it inside the manufacturing processes.

Interdependence between modules is a concept that is influenced by other conceptual elements, especially standardisation and functionality. Modules interact only between standardised interfaces (Baldwin and Clark, 2000; Zirpoli and Becker, 2011), because inconsistencies in this situation undermine coupling and connection between product modules, preventing its building as a whole. It is undertaken here that interdependences between modules need to be developed during product development early phases and then transferred to the production line, suggesting a MID to MIP direction.

Regarding the suppliers involvement on design (co-design), Jacobs et al. (2007) defends that product modularity has direct and indirect effects on cost, and indirect effects are result of higher suppliers' integration and design and manufacturing product integration. In this sense, one can affirm that suppliers' involvement on vehicle design with the OEMs enhances modularity both in design and in production, since suppliers will not only participate in the assembly process, but also in the early stages of product development processes.

The last concept found, product platform, is established during product development process, in order to obtain greater modularity benefits such as product variety at low costs, sharing commonalities in modules/components along various vehicle models and brands, lead-time reduction and a more agile response to market demands. Product platform usually is defined during the product development process, i.e. prior to develop the production process to build all vehicle variants from the planned product platform.

However, when companies change their product platform structure, significant investments on the production processes are needed. Mercedes Benz (2014) example (cited in section 3.1) is one of the evidences that corroborates this relationship between MID and MIP through product platform development. Finally, Figure 1 shows a proposed framework with the identified conceptual elements involved in the relationships between MID and MIP and the possible trajectories of these causal relationships.

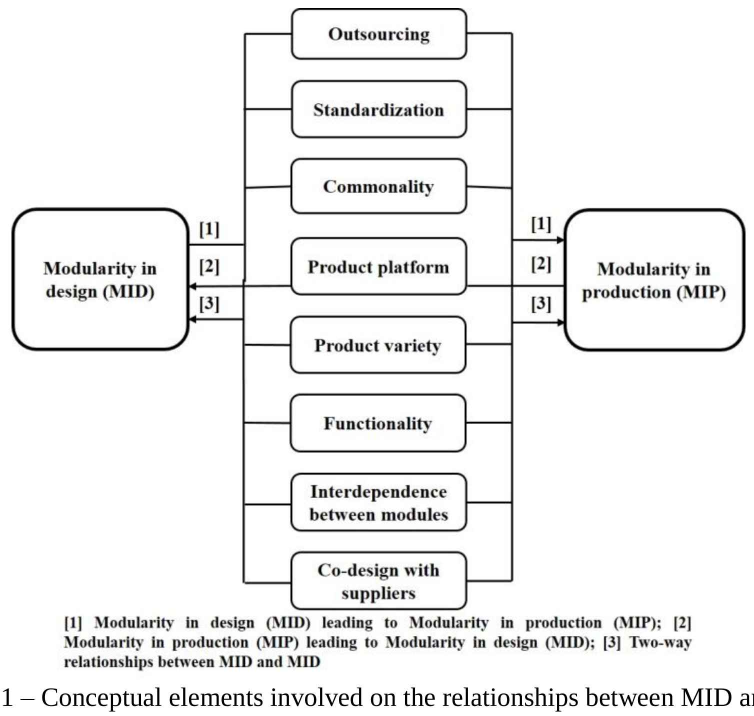

Figure 1 – Conceptual elements involved on the relationships between MID and MIP

3.2. MID and MIP: The Brazilian automotive scenario

Since the automotive industry introduction in Brazil, significant changes in relationships between companies working in this supply chain took place, especially regarding the location and positioning of product development activities and organisation of production processes (Salerno et al., 2009). With the arrival of new manufacturers, Brazil returned to a prominent and important position globally, mainly for small and medium vehicle manufacturers in Latin American market (Toledo et al., 2003). In addition, new products were introduced in the local markets, expanding shopping alternatives for consumers and driving companies already established in Brazil to conduct improvements in their manufacturing processes and product development activities, aiming competitive prices, better quality and innovation (Toledo et al., 2003).

The automotive industry around the world has also joined the ‘movement to modularity’, and in recent years, a number of firms have implemented various approaches to modular design and production (Sanchez, 2013). The same happened with Brazilian companies, where the most classical case is the renowned modular consortium in Resende (Ramalho and Santana, 2002), which has a strong supplier integration with the automaker within the plant. Therefore, modularity’s conceptual element ‘co-design with suppliers’ is strongly applied in this case. Ramalho and Santana (2002) state that the unique feature of the plant’s production system rests on the relationship between the assembler (VW) and its component suppliers. These were involved in a joint enterprise to establish a ‘modular system’ of production. In this system, the component suppliers finance a part of the factory and organise the assembly of their components on site. As such, the assembler has the main role of coordinating production and marketing the vehicle.

4. Discussions

One of the difficulties found in this study is the variety of “modules” definitions used in the automotive industry as well as in other industries. This conceptualisation’s lack of alignment, along with a vague understanding about modularity concept, might bring issues especially during empirical studies and practical adoption of modularity within companies. Therefore, it may be pointed out the importance of establishing clear conceptual definitions of “modules” and “systems”, avoiding inconsistencies on studies regarding modularity, especially when conducting empirical research on companies.

This study enables to observe that there are, in high or low extent, clear connections between MID and MIP. Although some studies argue that it is possible to structure some modularity typology without necessarily influencing another, most publications consider that structuring modular product architecture brings technical and organisational impacts to production modularity and vice-versa. In this sense, evidence suggests that usually product modularity is prioritised and later modularity concepts are used in production, simplifying manufacturing processes. This occurs especially with new products, when designers and engineers have more autonomy to build product and/or platform architecture. Additionally, it is noticed that relationships between MID and MIP can be stronger if managers and engineers involved have a mature knowledge about modularity principles and concepts, considering not only technical aspects but also strategic and mid- and long-term goals.

5. Conclusion

This paper offers three main contributions: establishing in a systematised way the causal relationships trajectories between MID and MIP, analyse what are the specific conceptual elements involved in MID and MIP relationships and offering some propositions of how these cause and effect relationships can increase practical and/or managerial implications. Considering that relationships between MID and MIP vary according to each company's context, it is proposed that the trajectories on building MID and MIP depend on the focus of each OEM as well as the context where they are involved and the focus of each developed vehicle.

As theoretical contributions, the results show that it is not possible to establish only a one-way relationship between MID and MIP, considering that these relationships have conceptual elements that affect both product and organisational architecture. The importance of these relationships regards on observing what companies prioritise more (MID or MIP). From a theoretical perspective, literature is still not well developed concerning relationships and directions between MID and MIP. There is still more issues to be explained, and the conceptual elements involved in these relationships can be a way of demonstrating how MID and MIP are related.

Since this study is a theory-building effort, further empirical study is needed. Some interesting insights about the practical implications of MID and MIP relationships might emerge through this next step. In addition, the continuity of this work intends to check if practices are aligned or conflicting to what literature already shows.

The following opportunities for further studies are suggested:

i. Explore how MID and MIP are linked within the Brazilian automotive context, considering the platforms and vehicles most recently developed specifically in the context of local markets, since Brazilian automotive context is still scarce regarding literature and research focused on MID and MIP relationships. In addition, Brazilian automotive industry is an interesting field regarding application of modularity concepts and studies in this context might bring relevant contributions to the MID and MIP relationships subject;

ii. Compare product and production modularity relationships in the Brazilian automotive industry, where the topic is considerably recent, to other developed markets, such as the European automotive industry, in order to analyse the main differences when applying modularity in such different contexts.

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