Modularity in design and production relationships: a field study in two automakers

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Abstract

Modularity-in-design (MID) and modularity-in-production (MIP) relationship has been gaining the attention of scholars and practitioners along the years. However, the literature does not specify how this connection occurs and its implications. This paper analyzes the relationship between MID and MIP within the automotive scenario and investigates its main technical and organizational implications. Through an abductive, matched pair case study carried out in two large automakers, the study gathered data from interviews, on-site observations, and field notes from all interactions within the plants. The paper indicates that (i) both automakers prioritize modular design before modular production, characterizing a product-related approach, and (ii) the investigated automotive companies have different approaches when developing MID. One automaker focuses on product functionalities to develop the modules; the other company dedicates efforts towards a MID-MIP relationship through the industrial condominium concept. Results indicate significant propositions to be tested regarding MID-MIP connection, with original insights from two make-to-order (MTO) automotive companies.

Keywords Modularity · Modular design · Modular production · Automotive industry

1 Introduction

Modularity has been applied extensively in design and production activities within the automotive industry, which corresponds to the most significant change within the sector [1–3]. Modular platform adoption by automobile manufacturers amounts to a revolution in product architecture in the automobile industry, thus gaining importance in this market segment [2]. Like any other strategies and methods, decisions about modularity-in-design (MID) and modularity-in-production (MIP) significantly affect the development costs of car projects, implying that modularity has a substantial impact on the automotive supply chain [1, 4].

As such, the MID-MIP relationship has become a prominent issue in the automotive industry over the years [1, 2, 5–9], including, for instance, the coordination between product design and manufacturing processes (e.g., [1, 7, 9, 10]). Modularity is usually a relatively well-known topic in the automotive industry. However, research focusing on the connection between MID and MIP is still limited, especially in terms of how automakers may connect those modularity typologies in practice, even though previous research has stressed the importance of this subject and issued a challenge regarding those relationships (e.g. [1, 6, 7]).

Having a MID-MIP relationship is not exogenous. It is a strategic choice, endogenous to every car maker. The relationship depends on the product strategy and many other variables, as argued previously by [11]. However, [10, p. 206] adds that “fewer firms clearly understand how modular design and development processes have to be structured and managed in order to obtain the full strategic benefits
available from modular product strategies.” Thus, MID-MIP relationships are still unexplored in terms of what are and how technical and managerial variables influence them. Previous literature suggests some antecedents and consequences: for instance, modularity is not developed in the same manner in Western and Japanese companies; Western companies focused on MIP (mostly through outsourcing), with impacts such as inconsistency or conflicts between modular design and modular production [4]. On the other hand, Japanese companies focused on in-house MIP, in order to establish MID-MIP relationship through functionality and conformance quality of modules, which are assembled on in-house lines [4].

Given that Western and Japanese automotive companies have been following divergent ways in implementing modularization, obviously their product architectures, production process hierarchies, and boundaries between in-house operations and outsourcing could be diverse [12]. The constant challenges that must be surpassed are the lack of integration capability of automotive suppliers [4] and the automobile companies’ persistently integrated manufacturing operations and design [11], as well as the relationship between MID and manufacturing decisions [2, 3, 6, 13]. Thus, it would be important to cast light on what are the variables affecting MID-MIP relationship decisions in automotive companies and what are the technical and organizational impacts of those decisions. Based on those arguments regarding the introduction of modular platforms into automobile design and manufacturing, this study formulated the following research question: How do MID and MIP are related to one another and affect strategic decisions regarding product design and manufacturing processes in automotive companies?

This paper explores the relationship between MID-MIP in the automotive industry. It analyzes how different MID-MIP relationships strategies affect two automobile companies. The paper is structured as follows. Section 2 describes the theoretical background regarding MID-MIP relationships in the automotive industry. Section 3 outlines the research methods, and Sect. 4 addresses the findings from the field study. Section 5 gives a discussion of the findings. Finally, Sect. 6 concludes the paper.

2 Modularity-in-design (MID), modularity-in-production (MIP), and their relationships in the automotive industry

This section presents the literature background that supports the paper. It is subdivided into two parts: (i) MID and MIP constructs definition and (ii) evidence regarding MID-MIP relationships in the automotive industry.

2.1 MID and MIP constructs

Before understanding the theoretical background regarding MID-MIP relationships, it is essential to point out MID and MIP concepts. MID is the product design defined through a system decomposable into various highly interdependent systems [14]. Still, according to the authors, the decomposition of a system requires three elements:

- An architecture that specifies what modules will be part of the system and their functions
- Interfaces that describe in detail how the modules will interact, including how they fit together and communicate
- Standards that test a module’s conformity to design rules and measure the module’s performance relative to other modules.

Therefore, MID is defined as choosing the design boundaries of a product and its components so that design features and tasks are interdependent within and independent across modules. The variables related to this MID definition are (i) component commonality, (ii) component combinability, (iii) function binding, (iv) interface standardization, and (v) loose coupling [15]. Furthermore, [7] add the possibility of interchangeable elements that enable configuring a wide variety of end products through loose coupling, ease of disaggregation, heterogeneous output, and a one-to-one matching of function to a module. Additionally, evidence from literature states that modularity is related to standardization through commonality and product architecture [7].

Meanwhile, MIP means designing operational value streams that maximize separability and recombinability. In automotive operations, this might mean designing manufacturing and assembly to reduce the complexity in the primary process by employing sub-assembly, pre-fitment testing of modules, possibly transferring these activities to suppliers [12, 16, 17]. Also, this implies designing operations for scalability, using “modules” corresponding to self-contained bundles of resources and processes (e.g., production lines) mapped onto discrete production capacities [18, 19]. Modular production systems involve process modules characterized by standardized groups that have few strong organizational ties [20, 21], thus allowing decoupling and resequencing of processes and tooling with minor loss in functionality “because each process module functions as a relatively autonomous unit” [7, p. 126]. A process can be viewed as modular when each production operation is independent of prior operations [7, 22, 23].

Hence, this study understands MIP as the following: the incorporation of adaptable and reconfigurable tooling and
routings into production operations to meet heterogeneous demand effectively, allowing separability and reconfigurability; modular processes are characterized by the extent of use of flexible manufacturing systems, autonomous and independent process units, group technology, cellular manufacturing, and general-purpose equipment because all of these are related to ease of process reconfigurability; flexible manufacturing systems are those that can be changed readily in response to changes in product demand [1, 7, 12, 22, 23]. In summary, MID is characterized by the following variables: (i) separability, (ii) recombinability, (iii) pre-testing modules, (iv) possibility of transferring activities to suppliers, (v) standardized groups of processes, and (vi) independence between operations.

### 2.2 MID-MIP relationships in the automotive industry

Despite of the wide-ranging application of modularity concept in the automotive sector, there are still many challenges to overcome [1, 2, 10, 24], including the MID-MIP relationship. Current research has been pointing out different directions. Some outcomes suggest that MID may facilitate MIP decisions, claiming that changes in the modular product or platform structure of a vehicle influence its production [8, 25], demanding a production system to manufacture all vehicle variants [26], which means, for instance, more flexibility and agile tooling configuration for producing the vehicle variants. Those features, as argued by [7], indicate a MIP setup. Some studies even argue that MIP in process infrastructure might be an inevitable result of more MID decisions, which may facilitate companies’ organizational reconfiguration [2, 7, 25–27]. Hence, those authors argue that, in logical terms, MID leads to MIP.

On the other hand, there are some cases where MIP calls for a further product architecture redesign, i.e., MIP may demand changes in MID decisions [28]. For example, companies might have to consider the manufacturing structure before designing a modular architecture (e.g., [29, 30]), with a specific type of product architecture being conditioned by each company’s organizational capabilities [30]. This means that it is necessary to evaluate all process conditions and structures before establishing the design of a new modular product architecture. Changes in the hierarchies in production systems and inter-firm systems create tensions with product architecture, encouraging its redefinition [2]. Therefore, other studies have been defending that the changes towards separability, recombinability, flexibility, loose coupling, process independence, and autonomy would affect decisions regarding component commonality, combinatoriality, standardized interfaces, and function interactions.

Nevertheless, there are occasions when MID-MIP relationships may have a two-way trajectory (e.g., [1, 6, 31–33]). Such MID-MIP relationship trajectory and its respective organizational effects depend on the unit of analysis considered [32], suggesting that there are contingencies that moderate MID-MIP connection. MID-MIP paths result from [31]: (i) previous and current configuration of the examined organization; (ii) product architecture characteristics; and (iii) rate of technological change and organizational learning.

Modularity can be improved when its concept extends to manufacturing processes [9]. In fact, there is currently more consensus indicating that higher degree of MID over time enables manufacturing structure changes towards a higher MIP level, i.e., product architecture can generate technical and organizational changes in production processes, which characterizes a product-related approach. Furthermore, some authors claim that modularity choices in product development processes affect further decisions and activities regarding manufacturing processes, enabling MIP (e.g., [2, 7, 29, 34]). However, it is noteworthy that companies may have different goals when applying modularity, which may lead to distinct levels of relationships between MID and MIP and different strategies and objectives [2, 10]. Table 1 summarizes the theoretical evidence regarding the MID-MIP interrelationship, while Fig. 1 indicates this interrelationship in terms of product flexibility and production volume.

Some practical examples of MID-MIP relationship can be found in the literature. Mercedes-Benz controls its central plant and reduces their production lines and standardization costs, working towards a production by product architectures [35]. The company’s strategy is that the sedans of the S-, E-, and C-class are based on a common rear-wheel-drive architecture. There is also a front-wheel-drive architecture for the complete compact car family, an architecture for SUV models, another for sports cars, and an architecture for the drive train [2, 36].

Renault-Nissan developed their MID-MIP relationship through the Common Module Family (CMF) platform, an engineering architecture that covers vehicles from both brands, from one or more segments, based on the assembly of compatible “big modules” (Fig. 2): engine bay, cockpit, front underbody, rear underbody, and electrical-electronic architecture [35]. CMF focuses on sharing standardized interfaces, modules, and functions among various platforms, suggesting that the alliance can involve several product platforms through the “carry-across” concept [37], thereby achieving both greater product variety and lower costs through large-scale production and assembly of common body modules and related components [38].

In the case of Volkswagen, the MQB modular platform allows variations in all the longitudinal dimensions except for the distance from pedals to front axle (front and rear overhang and wheelbase), due to its three compatible structural modules: front and under-body chassis, front floor, and rear floor [2, 39]. From the product design perspective, this MQB platform
(Fig. 2) is made up of three structural modules with different options (three front and under-body chassis, five front floor, and four rear floor) and allows variations in track width and in all the longitudinal dimensions except for the distance from pedals to front axle (front and rear overhang and wheelbase). From the manufacturing network perspective, this new modular platform makes it possible to produce its segment C and D vehicles in new locations, thus coming closer to customers in today’s markets [2].

As can be seen in this section, evidence suggests that there are connections between MID and MIP in the automotive industry, i.e., decisions regarding modular product systems have a significant technical and organizational impact on companies, suggesting that there are consequences in MIP decisions (and vice versa in some cases). However, there are few details about how automotive companies understand MID-MIP and how they obtain advantages through those relationships in practice. The following section presents the research methods to carry out this study.

### 3 Research design

In this paper, we propose a case-based approach to support researchers in seeing new theoretical interrelationships and questioning old ones [42, 43]. The choice for a

| MID-MIP relationship trajectory | Highlights                                                                 |
|---------------------------------|-----------------------------------------------------------------------------|
| MID enabling MIP                | • MID leads to MIP [7]                                                       |
|                                 | • Product structure changes affect production demands and capabilities [8, 26] |
|                                 | • The strategic decision of adopting MID brings subsequent implications in MIP [1, 26, 34] |
|                                 | • Modular products can facilitate organizational reconfiguration of companies [27] |
|                                 | • MID decisions affect further definitions regarding MIP [1, 7, 26]          |
|                                 | • Production mobility among models from different segments is possible among plants belonging to networks by using a modular platform [2, 9] |
| MIP enabling MID                | • Companies must consider manufacturing structure conditions before MID decisions [1, 29] |
|                                 | • Changes in the supply chain and inter-firm interrelationships may demand product architecture redefinitions [12, 30] |
| MID-MIP two-way relationship    | • Benefits of modularity are contingent on design and manufacturing features and are closely related to the carmaker’s ability to use its production capabilities effectively [1, 31] |
|                                 | • The trajectory of the MID-MIP interrelationship depends on the unit of analysis under investigation [32] |
|                                 | • Product architecture characteristics, rate of technological and organizational learning at the intra-/inter-firm level, and the industry structure affect the MID-MIP interrelationship [31] |
|                                 | • Sometimes technological modularity (MID) pushes the organization; sometimes organizational modularity (MIP) induces a product architecture change [31] |
|                                 | • Western companies focus on MIP by reducing costs through outsourcing; Japanese companies focus on MID, relating it to MIP through functionality, standardization, and quality conformity [4] |

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**Table 1** Theoretical evidence of the MID-MIP relationship

**Fig. 1** Modular vehicle development [4]
case-based approach is because the research questions of this study embody an explanatory component (e.g., [44, 45]). A cross-case examination was carried out to further enhance data analysis [46], aiming to (i) deepen the investigation between cases [47], (ii) compare the phenomena investigated in both automakers [44], (iii) identify common and particular aspects between cases [46], and (iv) prevent researcher bias [45].

Defining criteria for selecting automakers is crucial to understand the investigation of phenomena [48]. The following criteria were used for the plants:

(i) Having proximity with suppliers to develop modules [2], to understand the MID-MIP relationship and indicate how the contingent factors may affect that connection [28, 49]

(ii) Having awareness and maturity in modularity adoption [10], to clearly understand specific MID-MIP relationship activities within companies

(iii) Applying modularity both in design and in production [1] through modular platforms [2], to analyze and indicate how the relationship occurs

Once these criteria were established, we analyzed which plants would fit them. This analysis led to a list of six automakers. The semi-structured questionnaire (Appendix A) supported the selection of automakers, which the authors invited to participate in this research. Four of them declined because they considered the research subject as a strategy for obtaining data. Thus, they just answered the questionnaire and did not accept to participate in the research sequence (interviews, nonparticipant observations, etc.). The other two companies agreed to be part of the field study. For purposes of confidentiality, these companies are referred to as Automaker A and Automaker B. [50] recommends 4–10 cases, while [51] suggests 6–10. Therefore, this study has limitations in terms of external validity of the results [45]. Nevertheless, this research shows the comparative analysis of the two automakers regarding specific issues of companies with similar context, activities, and focus (both are MTO passenger car assemblers). Therefore, the study aims to understand the phenomena involved therein and the contextual social dynamics [42].

### 3.1 Data collection procedures

Firstly, Automakers A and B filled in a semi-structured questionnaire to provide general information concerning modularity. The purpose was to gather standard modularity practices that would establish a preliminary ground on the MID-MIP interrelationship. An interview protocol was also developed (Appendix B), further revised by an engineering manager from another automotive company and by an academic expert. These professionals were chosen because of their extensive experience both in the automotive market and in the modularity application in the sector. This procedure helped to increase the protocol’s precision, cohesion, clarity, and relevance, thus supporting face validity [52]. After that, we conducted five interviews with managers and engineers to collect specific evidence about MID-MIP interrelationships, besides nonparticipant observation in both plants (head office and manufacturing facilities).

In both companies, the main reason to select the interviewees was their in-depth knowledge of product development and modularity application in the product design and manufacturing processes. Furthermore, they were directly involved with the design and production activities, which underline their deep comprehension of modularity. Table 2 provides an overview of the sources and information gathered from both automakers and the details of the respondents’ position.
| Source                               | Quantity and description                                                                 | Amount of primary data                                                                 | Motivation to collect                                                                 | Information gathered                                                                 |
|-------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Questionnaire answered by managers  | • General manager—Platform and Systems Engineering Department  
• Director—Project Engineering Department                                              | • 24 pages of 18 answered questions                                                   | • Collecting preliminary data regarding modularity application                        | • General data about modularity application in automotive companies                   |
| Interviews with managers and engineers | • General manager of the Platform and Systems Engineering Department (did not allow audio recording)  
• Project Engineering Department Director  
• Engineer from the Project Engineering Department  
• R&D manager  
• General manager—Product Development Department  
• Field notes from the platform and systems engineering manager from Automaker A (did not allow audiotape recording) | • 31 pages of narrative text, including:  
• Verbatim transcriptions (audiotape and videoconference interviews—Automakers A and B)  
• Identifying general aspects concerning modularity  
• Examining primary evidence regarding the MID-MIP interrelationship | • Decisions criteria considered when applying modularity to establish the MID-MIP interrelationship |                                                                                  |
| Site visits                         | • One visit, lasting two days (around 4 h on each day)  
• One visit, lasting two days (around 4 h on each day)  
• Around ten pages of field notes (on each visit) | • Understanding the engineering management and manufacturing decisions through in loco observations  
• Nonparticipant observation yielding insights into product design and manufacturing decisions |                                                                                  |                                                                                  |
| Additional questions (email and telephone) | 2  
1 | • Three electronic messages answering the questions  
• Collecting complementary data about product development and modularity application | • Additional primary empirical evidence regarding modularity  
• General information about product architecture and manufacturing processes |                                                                                  |
| Specific company websites           | 2  
2 | • Two pages of notes based on the websites’ information  
• Data about product architecture processes |                                                                                  |                                                                                  |
| Presentation notes                  | 1  
- | • Two pages of notes from a presentation  
• Collecting data regarding the company’s product design and management |                                                                                  |                                                                                  |
Data analysis was iterative; the authors double-checked the interviews and the questionnaires to revisit the information and see whether the data and analysis were sound. The study followed a combined approach based on the guidelines presented next [44, 47, 53].

Data preparation and organization

Data collected from the interviews through paper notes were electronically registered and organized right after conducting the interviews. Data collected from the questionnaire were prepared together with the field notes from the interviews and observations. Data from both evidence sources were aligned to further enhance analysis [54].

Data reduction and coding

Data-driven coding was used to look for concepts that emerged when reading the interview transcripts, as recommended elsewhere [55]. The first codes expressed themes in the informants’ language. Then, these codes were refined from theoretical insights throughout the analysis of the interviews, as supported by [44]. Data regarding MID and MIP’s conceptual elements and their relationship trajectories were checked during the data reduction and coding process. For example, the code “modules and process relationship” (MPR) was applied to the statement “[all manufactured vehicles] at this time, already have in its concept the modules’ strategy... it involves the product and its relationships with the manufacturing process. The relationship is a result of the modules’ and systems’ design” (Platform and Systems Engineering Manager). Thus, one can find a significant consistency between the codes and the informants’ definition of the modularization process. Coding also captured the main consequences (benefits and drawbacks) of adopting modularity, finding suggestive remarks about MID-MIP relationships and their results in each investigated company. Through a data sample of the study, Table 3 presents an overview of the coding process of this work.

Categorization and identification of interrelationships

This step identified the connections among the conceptual elements found during the study. The identification of the conceptual elements used to analyze MID-MIP relationships occurred during the literature investigation. Hence, those conceptual elements were established a priori and served as the categories of analysis.

Data inference

Interviews, questionnaires, and field notes were scrutinized to build the results and analysis. MID-MIP relationships were examined using tools such as audio-textual analysis, ocular scan, word repetitions, keywords in context, cutting and sorting, constant comparison, and metaphors and analogies [54]. Then, the analysis indicates how MID-MIP relationships occur in the investigated companies through the conceptual framework verification, comparing it with the empirical data collected. This technique enabled the analysis of MID-MIP relationships and the demonstration of the framework in both automakers. Throughout this analysis, previous conversations with some key informants (mostly from other automotive companies that did not participate in this study) granted the authors’ confidence that the developing understanding was consistent with their experiences.

Case study findings

This section presents the findings of the case studies conducted in the two automotive companies, beginning with an overview of both investigated automakers, to present the findings of each case.

Overview of the investigated automakers

Both companies are MTO organizations, and both examined plants assemble mainly passenger cars, being among the top five bestselling light vehicle brands in Brazil. The two companies also answered (questionnaire) that they have

| Table 3  Coding process for interviews (based on [55]) |
|-------------------------------------------|-----------------|------------------------|
| Transcription (raw data): Platform and Systems Engineering Department—Automaker A | Preliminary data-driven coding | Final code |
| ‘All manufactured vehicles, at this time, already have in its concept the modules’ strategy. It involves the product and its relationships with the manufacturing process. The relationship is a result of the modules’ and systems’ design’” | • Modules’ concept | • Module and process relationship (MPR) |
| ‘Product design ‘calls’ for ‘how to do’ and ‘what is needed’ to enable the building of the best final product possible. We have some issues that we consider while manufacturing processes are in progress, to make some design adjustments (e.g., ergonomics). However, in most situations, it is the product architecture and module decisions that give the guidelines to improve the manufacturing lines’” | • Product and process relationship | |
applied modularity both in design and in production for more than 10 years, which indicates maturity in this concept. Automaker A operates in southern Brazil since 1998. It has around 6300 employees and has produced around 3 million vehicles to the USA and national markets, with a 9.61% market share in the passenger car segment in Brazil. The company has engineering and design centers, enabling a product development process to meet specific requirements. Automaker B operates in northeastern Brazil and has begun its operations in 2001 with the introduction of new product architecture and manufacturing concepts. One example of these concepts is the industrial condominium, a configuration where some suppliers, chosen by the assembler, establish their facilities in the vicinity of the assembler’s plant and start to supply complete components or subsets [56]. A fundamental characteristic of the industrial condominium is the presence of the assembler as the director of the entire project. The company has around 7700 employees and an 8.7% market share in the domestic passenger car segment.

### 4.2 Case study findings—Automaker A

This company focuses on a MID to MIP relationship trajectory through the automaker’s “product-process conception system.” Evidence suggests that in terms of modularity objectives, this company focused on reducing product costs by increasing standardization and common and reusable modules/subsystems and components (as defined by Sanchez [10]). According to the Platform and Systems Engineering Manager, the primary motivation for such trajectory (MID→MIP) is that design modifications incur higher costs than production adjustments. From the assembler’s perspective, MID-MIP relationship starts when defining the product features, which cannot be restricted to one or two types of vehicles manufactured by the company. Still, the abovementioned manager understands that MID-MIP relationship is a natural result of the platform design. Modular product architecture decisions provide the guidelines for improving and adapting manufacturing processes:

Product design ‘calls’ for ‘how to do’ and ‘what is needed’ to enable the building of the best final product possible. We have some issues that we consider while manufacturing processes are in progress, to make some design adjustments (e.g., ergonomics). However, in most situations, it is the product architecture and module decisions that provide the guidelines for improving manufacturing lines. (Platform and Systems Engineering Manager—Automaker A)

All manufactured vehicles, at this time, already have in its concept the modules’ strategy. It involves the product and its relationships with the manufacturing process. The relationship is a result of the modules’ and systems’ design. (Platform and Systems Engineering Manager—Automaker A)

As specific conceptual elements adopted to shape MID-MIP relationships, Automaker A mainly explores (i) functionality, having product functions as the main background to define modularity and further product architecture; (ii) standardized and interdependent modules developed through product functions; (iii) commonality, sharing as many components as possible across vehicles on the same platform; and (iv) outsourcing, transferring the design and manufacturing modules accountability to first-tier suppliers. Automaker A defined 30 functions in its product platform, distributing the modules across those functions and allocating the respective suppliers responsible for each module. Additionally, Automaker A applies commonality to enable the development of more standardized interfaces and interdependencies to ensure a higher number of common modules and parts across products, allowing the outsourcing of some engineering and manufacturing activities.

Through those decisions, Automaker A can define modules’ functions and interdependencies among them. Then, the company builds the modules and the components that will be common to certain varieties of vehicles. These decisions enable the grouping of modules to facilitate the identification of the demanded suppliers’ competence for each system development, their respective functions, and the suppliers responsible for developing them. Figure 3 illustrates MID to MIP decisions in Automaker A.

Despite functionalities and modules’ interdependence decisions, few changes occurred in the manufacturing processes towards MIP. Changes identified in Automaker A indicate (i) an increased automation in processes, (ii) a division into manual and automated process modules, and (iii) an avoidance of isolated operators within production lines. Those modifications were incremental due to the company’s economic conditions and difficulties to radically change the manufacturing layout. Mostly, the company focused its investments on raising its productive capabilities, replacing equipment, and modifying technology:

We had some changes in our layout: grouping manual modules and automated modules with robots. Then, we transformed the logistics supplying structure into picking areas, which facilitated modules’ supply. (Design engineering interviewee—Automaker A)

Thus, little evidence was found regarding MIP→MID relationship logic trajectory. Automaker A usually faces ergonomics issues during the definition of manufacturing processes. Thereby, design engineers analyze the conflicts to correct identified problems. However, Automaker A
considers ergonomics without necessarily addressing modularity decisions. It is a product prerequisite that they treat to meet customers’ demands. In product variety decisions, the company analyzes market demands before building all variants needed according to customers’ requests, as mentioned by one interviewee:

The market leads product variety. It is not an aspect that we decide based on modularity. It does not make sense to build more product variety if the market is not calling for it. (Engineering Manager interviewee from Automaker A)

That is, modularity might be the enabler, but not the driving strategy to offer higher or lower product variety level. The company decides how to consider such information on MID definitions before an aftermarket analysis. Indeed, modularity had technical and organizational impacts on the product and process decisions in Automaker A, as shown in Fig. 4. However, those impacts mentioned may not always be beneficial:

Modularity is the natural step after carry-over/carry-across and the previous step of system design. Furthermore, all of these strategies profoundly impact lifecycle product management and, consequently, profitability, longevity, and the company’s brand image. Let me be clear that ‘having an impact’ does not \textit{per se} assume that it will only be positive, given the recent industry recalls that have affected millions of units worldwide. (Platform and Systems Engineering Manager—Automaker A)

4.3 Case study findings—Automaker B

According to the product development manager, Automaker B has a MID-MIP relationship in decision-making, in which MID decisions in product design phases enable MIP characteristics. Automaker B’s goal was to develop modularity as a strategic integration, aiming at setting market, technology, and business strategies through its new modular product platform (as suggested by Sanchez [10]). The engineering department decides the modular design in three subsystem levels: the first level is called “blocks,” designed through a so-called Global Product Development System. The product development manager explains that the “blocks” compose what the company determines as “systems,” understood as the “modules.” As pointed out earlier, the second level is the ‘subsystems–level 1,” which involves 15 modules that build up the vehicles’ platform. The third and last level is called “subsystems–level 2,” where they subdivide each of the 15 modules on their respective components. In the subsequent level, the company considers each part as modules’ components:

The seven blocks are the great modules of the platform. Then, we divide them into the other fifteen independent modules, which build the vehicles as a whole, interacting in preparation phases for assembling them. Some examples of those modules are the engine, suspension, fuel tank, electric system, and the exhaust system. (Global Product Development Manager—Automaker A)

Automaker B decides the modules’ functionalities and interdependencies among those subsystems before the
manufacturing and assembly requirements. At this stage, the focus is on establishing compatibility among platform systems (modules). The relationships between MID and MIP are defined afterwards:

[The systems] ... would be the modules. So, for example, I have the electricity module: the electrical harnesses, the body part, the front of the car, and the engine, it consists of a block, you know. Then there is a second block, which is the entire floor of the car. So it would be the entire floor of the car, with front and rear suspension, right (?), and everything that gets stuck in that, pipe, electrical harness, all of that is another system. (Global Product Development Manager interviewee—Automaker B)

Based on the bill of material, product function, and structure, we define the platform modules in order to prepare the engineering development to further reduce production costs and lead time. (Product Engineer interviewee from Automaker B)

This company connects commonality and standardization to outsourcing and co-design (supplier-related) concepts through the negotiation of standardized modules with global suppliers to increase commonality application (which is a mandatory rule in Automaker B). It enhances common component sharing and reduces individual costs when purchasing. The aim is to generate more economies of scale and standardize production processes as well as reducing changes due to fewer product design modifications:

Suppliers: Automaker B, it always works with global suppliers. So, for example, dampers. They do the quotation with their partner. OK. So, for example, for every new project, the shock absorber supplier will be Supplier X. So, you have a quality problem with Supplier X; it does not matter, you have to do the quotation with Supplier X. It is a targeted quote. ‘Yeah, but Supplier Y is cheaper’. You cannot; you have to go with Supplier X. Because they assume that as they trade all Automaker B volumes in the world, they are the cheapest. (Product Development Manager interviewee—Automaker B)

Therefore, modular product design starts defining the so-called blocks as the central basis for developing the other 15 modules both independently and associated with the automaker’s first-tier suppliers. Automaker B applies MID-MIP relationship through outsourcing and co-design with suppliers, with a predominant MID→MIP logical trajectory by selecting first-tier suppliers. It also has some MIP to

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**Fig. 4** Conceptual elements involved in Automaker A modularity decisions
MID features, mostly involving suppliers’ product manufacturing potentialities and limitations, such as flexibility and interdependence level of the manufacturing processes. The first-tier suppliers have the autonomy to decide which second- and third-tier suppliers will develop the subsystems and components that their modules demand. According to their competence, first-tier suppliers decide the components that will build the module or even propose some quality requirements to the automaker, increasing suppliers’ autonomy. In other words, suppliers become responsible for building their respective modules because Automaker B transfers the modules’ design (under specific predetermined criteria) and manufacturing processes to them (as responded by the automaker in the questionnaire).

The MIP perspective considers the plant as an industrial condominium, following the modular concept under assembly specifications, pre-assembly sequencing, manufacturing layout, and some suppliers’ contract terms. Automaker B manages the entire supply chain. Thus, the MID-MIP relationship emerges by associating the 15 modules to the respective suppliers. Figures 5 and 6 represent the modularization process of Automaker B based on the evidence found in the questionnaire responses and interviews.

Furthermore, during MID-MIP, the company focuses on standard production processes to build various modular variants through a conceptual development in terms of the product life cycle, reducing complexity and costs. However, these decisions might have some drawbacks. Since specific modules and components are under the responsibility of exclusive suppliers, quality problems or economic issues might generate significant technical and organizational issues, affecting a higher volume of products, with suppliers’ exclusivity leading to a lower possibility of overcoming the problems. Figure 7 depicts the framework of the MID-MIP relationship in Automaker B.

5 Discussion

This section is divided in two parts. The first examines the MID-MIP relationship in the investigated automakers and the second discusses possible contingencies moderating MID-MIP connection.

5.1 MID-MIP relationship in the two investigated automakers

In both cases, the findings characterize a product-related approach (i.e., MID leading to MIP), corroborating studies arguing that MID application is more developed than MIP in automotive companies [1, 7]. During the modular design phase, Automaker A established product functionalities and production requirements to build the product variants needed. In turn, Automaker B applied the “blocks” concept to connect the modules that compose the company’s leading product platform to evaluate the consistency among modules and determine the basic requirements for suppliers to develop and assemble the modules. Thereby, results also indicate that modular design intentionally aligned product...
architecture and manufacturing processes in both car assemblers, i.e., modularity affects both design and production decisions [1, 6, 7, 26, 33].

In the MID perspective, Automaker A makes its product architecture decisions based on product functionalities, disclosing its product-related approach, revealing that

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**Fig. 6** Modularization processes and decisions in Automaker B since the development of the product platform design: empirical example of the front suspension module

**Fig. 7** MID and MIP conceptual model based on Automaker B data analysis
the company focuses on functionalities’ definitions [30] and standardized and interdependent modules [24, 43] in order to share them through various vehicle brands. That is, Automaker A uses standard and well-defined interfaces as coordination strategies for building cars and for their manufacturing processes [49].

Although there seems to be a MID-MIP relationship in Automaker A, the analysis shows that it is still limited in terms of technical and organizational effects on manufacturing processes (from the MIP perspective), thus prioritizing MID. Some scholars (e.g., [1, 2, 5, 7, 26, 34]) have argued that modular product design decisions would profoundly affect subsequent manufacturing operations towards a higher MIP. Evidence found out in Automaker A differs from the studies mentioned earlier. The changes carried out in production were restricted to few adjustments and settings in manufacturing, such as (i) increased technology and standardizing manual processes and (ii) automatized production modules, in addition to the minimization of isolated operators in each workstation. Thus, the few changes in terms of more flexible production systems are still a challenging issue [2, 33, 57].

Automaker A concentrated these changes on standardized production and independent processes (as supported by [7, 10]). However, those modifications are still distant from a MIP level as presented by [58]. The low level of modularity in assembly systems is one of the most critical challenges in mixed-product assembly lines [33]. Since there is an established manufacturing arrangement, the company has not faced severe modifications in its production processes. It corroborates [2, p. 709–710]: “The use of standard platforms over past years has made automobile networks fairly rigid from the points of view of both production mobility and the sharing of resources on a worldwide scale.” Although modularity is expected to support overcoming the issue of rigid structure in manufacturing networks [2], in fact, few changes were observed in Automaker A in the MIP perspective. Therefore, apparently Automaker A has not experienced all benefits expected from modularity (as argued by [24]).

Automotive companies needed severe internal reorganization and better coordination with suppliers to ease the shift to new modular solutions in both design and manufacturing processes [1, 33, 57]. Such a scenario occurred in Automaker B. There were difficulties in that direction because the developed product platform had changed due to the new vehicles’ development. This has affected production in terms of increased investment for more production flexibility and interdependence. Automaker B faced a more radical reorganization in its production systems than Automaker A, which is the reason why MIP features emerged more in Automaker B, suggesting higher maturity of implementation of this modularity typology. Flexible manufacturing systems is a relevant feature to develop MIP, and literature has been pointing out that importance [33, 57].

Accordingly, findings in Automaker B indicate a more mature MID-MIP relationship in relation to Automaker A. Through a new plant and platform development, the company could extract more advantages from modularity, such as increased compatibility within product architecture decisions and costs reduction through outsourcing and co-design with first-tier suppliers, which contributed to establish more flexible and autonomous manufacturing systems (MIP features). Additionally, Automaker B developed the industrial condominium concept. Thus, significant investments in technology, layout changes, and manufacturing operations occurred in Automaker B, characterizing a higher MIP level than in Automaker A.

5.2 Contingencies affecting MID-MIP relationship in the investigated automakers

Regarding product variety, this paper indicates that although other research highlights product variety as a modularity-supported concept (e.g., [59]), in fact, product variety is driven by the market, not by modularity decisions. In Automaker A, variety demands may be incorporated into modular design decisions but only in an aftermarket analysis. Similarly, Automaker B considers market demands before analyzing its level of product variety, yet with no modularity influence. Then, the company uses those demands in the modular design. Therefore, both companies seem to consider product variety in their strategic decisions before incorporating variety demands into MID-MIP relationship. The main advantage obtained from both companies is that modularity brought standardized interfaces and modules in their product platforms, which improved agility and compatibility when developing variety.

Concerning commonality and standardization, in the MID perspective, Automaker A focuses on functionality definitions first, to define the common modules across the various vehicle models developed by the company. Thus, the company applied standardized and interchangeable architectural elements through its product platform [7]. Those elements facilitate MIP decisions since they enable reconfigurable tooling and more flexible systems. However, Automaker A indicates that it did not obtain significant changes towards MIP, restricted to separating the production modules into manual and automated, as well as avoiding isolated operators in the workstations. Thus, Automaker A faced limitations when developing MIP because the changes were restricted to manage manufacturing processes towards reducing product costs. However, this automaker had an objective to reduce product costs;
therefore, MIP decisions, although limited, seem to be coherent with the company’s objective.

On the other hand, Automaker B defines its product platform architecture on a physical subdivision, where they subdivide the seven blocks into fifteen subsystems (called as “modules”) distributed through fifteen first-tier suppliers. Apparently, the company prioritizes the physical interfaces and interactions among the modules. Each of the suppliers is responsible for the respective component suppliers (second and third-tier suppliers), being also responsible for the manufacturing processes. Automaker B focuses on managing the entire supply chain. Thus, Automaker B explores the industrial condominium concept, which is tightly related to MIP [56, 58]. The automaker’s objective was focused on strategic integration (as supported by Sanchez [10]), which suggest that the industrial condominium approach is aligned with the company’s purpose when applying modularity.

Through co-design and outsourcing, while Automaker A has more local and various suppliers in its supply chain, Automaker B is more restricted in its organizational management since it has fewer (however, global) suppliers to manage. Later decisions concerning the modular architecture make module assembly more autonomous and independent [7]. Both organizational structures have embedded benefits and limitations. Automaker A has more suppliers for similar components, as negotiated according to each local supplier’s best price. One difference of negotiating locally is greater flexibility for changes when facing quality issues since it allows rapid changes in suppliers (if necessary), besides enabling the development of local suppliers due to decentralized decisions [60].

Additionally, Automaker A, on one hand, has more flexibility to change its suppliers and to manage quality problems when inconsistencies occur in MID and MIP activities. On the other hand, there are higher costs involved in managing a more significant and more complex supply chain and significant adjustments needed in the production processes. Automaker A also faces more complexity to manage quality conformity and suppliers’ activities since the company centralizes most of its product requirements.

Meanwhile, Automaker B has more limitations in managing product and process issues when they arise since its supply chain involves global suppliers. Additionally, it is harder to change them quickly due to the contracts established with those suppliers (first-tier). Notwithstanding, the company has more economies of scale due to the global provision of modules and components, enabling it to reduce costs and establish a medium/long-range contract to build various vehicles and brands from its current and future product platforms.

Therefore, this paper identifies another contingent factor: the decision between global and local suppliers. Automakers decide on a local or global component to match its business model and modules. Companies usually decide to use global suppliers to enhance economies of scale and thus enhance the globalization of production processes focused on cost reduction by using resources on a worldwide scale [2]. Negotiations with first-tier suppliers become facilitated because the modular product platform anticipates various vehicle models in the short, medium, and long terms. Thus, global suppliers would offer modules and components for all of these variants. The close collaboration between automakers and suppliers has a significant impact on modularity decisions, leading to implications for its strategy and innovation [28, 61]. However, quality and conformity issues may give rise to severe problems in the relationship between the automaker and suppliers because these challenges can be very costly for both parts.

Another issue that emerged from analysis is the connection between modularity and the company’s strategy. Automaker B seems to have more clarity than Automaker A in terms of strategic decisions regarding modularity. This is slightly related to their modularity’s objectives: Automaker A focused on solving technical aspects and reducing costs and time to market, while Automaker B used modularity to enhance its local engineering team and increase strategic integration, enhancing its alignment with the market, technology, and business model. The fact that evidence suggests that Automaker A faced more changes in the product design perspective than in the manufacturing perspective reflects its objectives through modularity. Thus, Automaker B seems to understand the current and future generation architectures as an essential part of the company’s strategic process [10]. This facilitated product platform development in terms of reusing platforms and modules and handling the modularity approach [2, 62].

Furthermore, Automaker B aims at a long-life-cycle platform, where the vehicles developed on the platform evolve. Thus, coordination between organizational units and product platform development is complex for automakers [63]. Thus, another contingency emerged: the alignment between modularity definitions and the company’s strategy. These decisions may be centralized (defined by the automaker’s headquarters) or decentralized (enabling more autonomy to the local centers to define variations resulting from the modular platform) [60]. After establishing the final project and its manufacturing processes, changes in the manufacturing processes can occur to a greater or lesser extent in the future. Table 4 summarizes the analysis and discussion from both automakers.
Table 4 Summary of MID-MIP contingencies and implications in Automakers A and B

| Modularity objectives | Automaker A | Automaker B |
|-----------------------|-------------|-------------|
| Reducing costs and time to market | Reducing costs | Enhancing production flexibility |
| Reducing costs | Restructuring local engineering capabilities |

Contingent factor 1: outsourcing/co-design

| Automaker A | Automaker B |
|-------------|-------------|
| Automaker decides the suppliers and the whole module and component selection | First-tier suppliers have autonomy to build their manufacturing processes and select some module’s components and quality criteria according to their competence |
| Process quality criteria under automaker’s decision | Focus on global suppliers to global platforms to enhance economies of scale |
| Prioritization of local suppliers to reduce costs | |

Contingent factor 2: standardization/commonality

| Automaker A | Automaker B |
|-------------|-------------|
| Extensive commonality to comply with as many vehicles as possible, reducing manufacturing settings to build the modules | Negotiation with global suppliers |
| First-tier suppliers have autonomy to build their manufacturing processes and select some module’s components and quality criteria according to their competence | Increased commonality among various vehicles in the same platform |
| Focus on global suppliers to global platforms to enhance economies of scale | More common machinery settings to build various modules/components |

Contingent factor 3: functionality/modules’ interdependencies

| Automaker A | Automaker B |
|-------------|-------------|
| Functions linked to the modules, which were associated and distributed among suppliers | Compatibility analysis between “blocks” and modules before building the prototypes |
| Functionality decisions managing interdependence between modules | Seven “big modules” divided into 15 modules, associated with first-tier suppliers |
| 30 functions guided the product platform structure | |

Modular design implications

| Automaker A | Automaker B |
|-------------|-------------|
| Increased standard modules and components among various vehicle models; reduced design and production costs | Increased compatibility process among modules, reducing inconsistencies |
| More common modules and components, enabling costs reduction | Increased alignment between platform architecture and manufacturing processes through quality tools (e.g., failure mode and effect analysis) |

Modular production implications

| Automaker A | Automaker B |
|-------------|-------------|
| Few changes/implications | Considerable changes/implications |
| Production separated into manual and automated labor modules | Outsourcing assembly activities to suppliers allowed higher autonomy in production changes |
| Future changes in the product platform will affect manufacturing processes (limitedly) | Future changes in the product platform might affect manufacturing processes considerably |

Other contingencies

| Automaker A | Automaker B |
|-------------|-------------|
| Selection of local or global suppliers | |
| Local suppliers: more agile management with changes when issues occur; greater and more complex supply chain to manage | |
| Global suppliers: more competitive costs and greater integration between OEM and suppliers; global quality problems when they occur | |
| Alignment between modularity decisions and strategic planning—related to modularity goals and the company’s maturity level | |
6 Conclusions

This study has investigated MID-MIP relationships and their contingencies and implications in two car manufacturers. The first contribution of this paper is more theoretical and identifies the constructs related to modularity, indicating a prevailing product-related approach, i.e., MID decisions have technical and organizational impacts on decisions about moving production settings towards MIP in both car manufacturers.

The second contribution of this study is in both the theoretical and managerial perspectives, mapping situations in which modularity definitions result from other choices (e.g., the relationship between product variety and market analysis). The analysis also raises other decisions that do not depend on the market context (e.g., economies of scale in global platforms). Additionally, such investigation may cast light on the contingent factors that affect MID-MIP application in automakers. Thus, factors such as (i) market demands, (ii) current production structure capabilities, (iii) suppliers adopted (global or local), and (iv) modularity objectives (MID-MIP) are some of the emerged contingencies.

As a third contribution, this paper also shows that MID and MIP relationships may reduce incompatibilities and increase synchronicity between modular design and production. The study indicates that both car manufacturers align modular design definitions with their production capabilities, though mostly with limited adjustments in terms of the MIP concept. These decisions may prevent themselves from planning MID without considering further implications in manufacturing processes (and vice versa), which could create severe inconsistencies involving product design, manufacturing requirements, production dynamics, capabilities, and investments needed.

However, this paper has some limitations. As mentioned previously, the focus of the paper was on MTO companies. Therefore, it does not consider make-to-stock, engineer-to-order, and assembly-to-order environments, which would be a potential opportunity for further research. Moreover, this is a field study conducted in two companies, which restricts external validity of the findings, even though a cross-case analysis was conducted in order to minimize this restriction. Future research would be relevant to delve deeper into how the contingent factors identified affect modularity application in automotive companies considering the suppliers’ perspective.

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