The new automobile modular platforms: from the product architecture to the manufacturing network approach

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Abstract: This paper analyses the key factors for the adoption of the new automobile modular platforms through an eclectic perspective linking the product architecture with the manufacturing network approach. An exploratory analysis of the European production networks of seven automobile manufacturers shows that the benefits of the modular platforms' adoption depend on two factors: the degree of platform modularity and the manufacturing issues of each carmaker —product portfolio, production volumes and network size. The results indicate that the degree of modularity of the platform chosen should be aligned with the manufacturing issues; otherwise, benefits might not reach expectations.

Keywords: Automobile industry; Manufacturing network; Product architecture; Modular platforms; Modularity.

1. Introduction

Many automakers have been manufacturing product families based on platforms since the 1960s (Cusumano and Nobeoka, 1998; Jetin, 1999; Muffatto, 1999), developing this strategy over the years. One of their main targets has been to reduce and standardise platforms in order to gain efficiency in design and development processes, and greater economies of scale in production and sourcing (Wilhelm, 1997; Becker and Zirpoli, 2003; Korth, 2003; Suk *et al*., 2007). However, a new generation of platform has been emerging since about 2010. Automakers are now introducing modular platforms, which have a new, scalable design that allows the structural dimensions of this basic element of the automobile to be varied (Buiga, 2012; Schuh *et al*., 2013). Roughly speaking, the aim of such modular platforms is to combine the advantages of modularity (Ulrich, 1995) with those of the platform (Gawer and Cusumano, 2002).

The automobile industry is not the sole sector interested in modular platforms. Since the pioneering work of Wheelwright and Clark (1992), many researchers have tried to understand the strategic use of such platforms (Gawer and Cusumano, 2002) and/or their impact on certain specific issues such as innovation rate (Langlois and Robertson, 1992; Baldwin and Clark, 2000) or design costs (Garud and Kamaraswamy, 1995). Some works have also pointed out the limits or dangers of modular strategy, from the point of view of competition (Ethiraj *et al*., 2008), specific issues like product integrity (Takeishi, 2002) or firms' boundaries (Brusoni *et al*., 2001). In fact, according to Gawer (2014), there are two main intellectual traditions for studying platform strategy: economists who try to understand what modular platforms change from a demand perspective (a market approach), and engineering scholars who focus on technological issues and are mainly interested in innovation (a product architecture approach).

Nevertheless, an eclectic perspective is necessary. In this paper we return to the initial reason for creating platforms, manufacturing issues, a core consideration for the automobile industry. It is somewhat surprising that such issues do not receive greater coverage in the literature, because modularisation in the automobile industry emerged initially as a way to improve production efficiency. The initial goals of automakers were to optimise the assembly process (MacDuffie, 2013) and to improve production flexibility (Salerno, 2001). Moreover, Frigant (2011) suggested that the first version of a modular platform (we will call it platform 1.1) was not necessarily efficient in terms of production cost. The question is, will the new generation of platforms provide an answer to the production challenge? This paper studies the link between production efficiency and modularity, taking into account the production capabilities of automakers. The main goals when introducing a modular platform include improving scale and scope economies, and operational flexibility (Lampón and Cabanelas, 2014; Lampón *et al.*, 2017). We aim to find out to what extent technical and production factors determine the benefits that can be obtained in manufacturing network outputs when automobile manufacturers adopt modular platforms.

This paper offers two main contributions. First, it explains why modular platforms are appearing now and why it is necessary to introduce production efficiency issues in the research agenda (rather than focusing solely on competition or innovation). Second, using new data from a survey, it shows that the benefits of a modular strategy for network manufacturing outputs depend not only on the design of the platform itself and its modularity, but also on the production issues of each manufacturer.

The remainder of the article is structured as follows. The first section reviews the modular platform concept, the benefits of adopting the modular platform strategy and theoretical aspects behind the influence of product architecture and production issues on manufacturing network strategic outputs. The second section studies the determinants and the impact of the adoption of modular platforms in European automobile production networks. The last section draws the main conclusions and describes some theoretical and practical implications of this research.

2. Literature review

2.1. The modular platform concept: from Platform 1.0 to Platform 2.0

The platform concept is not a novelty in the automobile industry, which has to deal with a very old dilemma: how to reach niche-market consumers while minimising production cost. The basic answer is through economies of scope (combined with economies of scale). This is why the foundations of platform strategy can be associated with General Motors under the management of A.P. Sloan during the 1920s, when it boosted the "commonisation" of parts between some brands of its multi-nameplates group (Raff, 1999). From the 1960s onward, most automakers (American, European and Japanese) tried to achieve this complementarity between scale and scope economies by sharing a growing number of parts between an increasing number of models (Jetin, 1999). To do this, they created the platform concept, but the transition path was slow. The rate of adoption differed for each automaker, depending on its technological knowledge, its strategic objectives and its own structural characteristics — number of brands, internationalisation, etc. (Chanaron and Lung, 1999). There was no dominant platform design (Abernathy and Utterback, 1978), and no single definition, either in general (Baldwin and Clark, 2009) or among automobile manufacturers (Muffatto, 1999; Ghosh and Morita, 2002; Simpson *et al.*, 2006; Mahmoud-Jouini and Lenfle, 2010). In fact, although the platform is a commonly used concept in the sector, the literature reflects different definitions of it as a physical element. For example, Muffatto (1999) considers that the platform means the core framework of the automobile in which the basic element is the underbody, made up of the front floor, underfloor, engine compartment and frame. According to Ghosh and Morita (2002), it can also include other components, such as the drive train and axles, and Muffatto and Roveda (2000) add the suspensions and power train. Setting these differences aside, the platform concept used in this research shares the product and process approaches described in the literature. A platform comprises a set of assets shared by a variety of products (Robertson and Ulrich, 1998) that are physically compatible in manufacturing processes (Muffatto and Roveda, 2000).

A process of reduction and standardisation[1] in the 1990s led to the development of a single standard platform —"platform 1.0"— for different models in the same segment (Holweg, 2008), with a standard design and permanent structural dimensions. It thus became possible for a large proportion of the components and systems to be the same for all the models assembled on the platform (Korth, 2003; Patchong *et al.*, 2003; García *et al.*, 2005).

In the early years of this century, this first generation of platform evolved along with the development of modular design (Sako, 2003; Takeishi and Fujimoto, 2003). Car manufacturers wished to create macro-components that they could include on several platforms (Volpato, 2004). It is now widely acknowledged that modularisation has deeply transformed the auto industry as a whole (Klier and Rubenstein, 2008; MacDuffie, 2013), and if we focus on platform strategy, modularisation helped develop the "platform 1.1" generation. As Gneiting and Sommer-Dittrich (2008:64) —engineers at Daimler— explained, "The old-fashioned approach of the platform strategy was usually limited to the standardisation of vehicle components (…) such as the use of the same chassis for two or more models of the same size class. In contrast, current modularisation concepts strive to build more complex modules or entire systems, which can be used in a large variety of derivatives of a size class and are enhanced with additional frame modules depending on the type, such as passenger car, station wagon, or coupé". This platform 1.1 makes it possible to improve the number of "common parts" (precisely those forming the macro-components) for different segments and to increase economies of scope and economies of substitution thanks to "carry-over" technologies (Garud and Kumaraswamy, 1995). But modularity did not fulfil all its promises (Zirpoli and Becker, 2011) because a car is a Complex Product System (Prencipe *et al.*, 2003). So, by the end of the 2010 or so, engineers were seeking to create a new generation of platform. After the era of modularisation, they wanted to create a modular platform.

Platforms 2.0 are really new for two reasons. From a design point of view, modular principles (fixed and decoupled interfaces, independence of the modules) are key points, allowing an increasing number of different cars to be built from a particular platform. Previously, automakers could design different models belonging to a single segment, what we call vertical variety. Now, the aim is to combine vertical and horizontal variety. These modular platforms adopt different configurations but start out from a single scalable design made up of modules and allowing the structural dimensions to be varied (such as the front and rear overhang, wheelbase and track width). This strategy for modularising the product architecture makes it possible to assemble not only several models from the same segment (same size) as with classic standard platforms, but also allows different models from different segments (different sizes) to be assembled on a single modular platform (Sehgal and Gorai, 2012; Lampón and Cabanelas, 2014).

However, it is important to learn from the past. Although the adoption of this Platform 2.0 is clearly a trend in the auto industry, carmakers' strategies are no longer the same, essentially because of manufacturing issues.

[1] In this standardisation process, automobile manufacturers mapped different platforms onto a common platform to support a variety of car models —standardisation of the platform components and the module interfaces— (Siddique and Rosen, 1998). The final result was a common platform which can accommodate a set of different car models almost without any changes in components or module interfaces (Whitney, 2004).

2.2. Modular platform strategy and manufacturing network outputs

The manufacturing networks approach (Shi and Gregory, 1998; Vereecke and Van Dierdonck, 1999; Gulati *et al*., 2000; Colotla *et al*., 2003; Rudberg and Olhagerb, 2003; Miltenburg, 2009) highlights four main network strategic outputs: accessibility, thriftiness ability, manufacturing mobility and learning ability (Shi and Gregory, 1998; Colotla *et al*., 2003; Miltenburg, 2009). Accessibility to supply sources, low-cost production factors, and the thriftiness ability gained by scale and scope economies favour the development of a more competitive network. Accessibility and thriftiness ability therefore define the network's efficiency (Shi and Gregory, 1998; Miltenburg, 2009), while manufacturing mobility and learning ability represent longer-term capabilities for network restructuring, especially manufacturing mobility defined as the operational flexibility that multinationals can use to adapt their production to volatility in the international environment (Kogut and Kulatilaka, 1994; Buckley and Casson, 1998; Rangan, 1998).

The manufacturing networks of automobile manufacturers are based on platforms, so that each plant only assembles models that share the same platform. Platform strategy brings advantages for the globalisation of production processes: the possibility of transferring production among plants —operational flexibility— (Robertson and Ulrich, 1998; Smith and Reinertsen, 1998), and cost reduction from using resources on a world scale —scope and scale economies— (Wilhelm, 1997). However, in the auto industry it has not been possible to fully enjoy these advantages. The trend over the last twenty years or so has been to dedicate production plants to one or two models only, making automobile networks fairly rigid from the point of view of production mobility because it is only possible to transfer production among plants within the same segment (Fleischmann *et al*., 2006). Today's new modular strategy brings an opportunity to take up the advantages of platforms (Lampón and Cabanelas, 2014; Lampón *et al*., 2017). On the one hand, economies of scope, understood as the advantages of adding different products to the global product portfolio (Kogut, 1989; Shi and Gregory, 1998), are greater, because a production network using a modular platform can include a larger number of models that share resources. On the other, plants in different segments can share the same modular platform so, depending on the number of plants in the network, greater operational flexibility becomes possible (Allen and Pantzalis, 1996; Tong and Reuer, 2007). Finally, by increasing the number of models manufactured and the number of plants in the modular platform production network, on the one hand production volumes across plants increase and, on the other, resources are shared among a larger volume of products, thus increasing the economies of scale.

2.3. Determinants for adoption of modular platforms: an eclectic perspective

The product architecture approach focuses on features related to product design, taking into consideration the opportunities and constraints of the manufacturing process (Ulrich, 1995; Fixson, 2005; Ulrich and Eppinger, 2008). The platform is key within this conceptual framework (Muffato and Roveda, 2000), as are the dimensional parameters (Cusumano and Nobeoka, 1992; Sköld and Karlsson, 2007), because too much commonality in physical product dimensions may limit the possibilities for product differentiation (Sköld and Karlsson, 2007). It is precisely in the modification of the dimensional parameters that the development of modular platforms has been most innovative. Unlike standard platforms where structural dimensions (e.g. front and rear overhangs, wheelbase and track width) are fixed, modular platforms are designed in such a way that these can be varied. Geometric variations in the platform depend on the degree of modularity or scalability of the platform so, to obtain greater variation in the structural dimensions, the platform has to offer greater modularity. 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 structural modules: front and under-body chassis, front floor and rear floor (Lampón *et al*., 2017).

The literature generally stresses that modularity can bring flexibility to facilities and processes (Ulrich 1995; Ro, Liker, and Fixson, 2007), and can support economies of scale and scope in the production of generic parts and in the use of common manufacturing resources on a worldwide scale (Garud and Kumaraswamy, 1995; He and Kusiak, 1997; Mikkola and Gassmann, 2003). Therefore, modularisation of the basic element (platform) on which the final product is built (automobile) can allow automobile manufacturers to obtain these benefits. It involves technical changes, and requires investments both for the development of the platform and for the re-design of the production plant's processes and facilities, but the final strategic outputs of the network may be greater.

These technical changes and investments can be found in two main processes and facilities in assembly plants: body-in-white shops working with a scalable platform and the flexibility and capacity of the final assembly lines, which are shared by a large number of products. First, a single-flow configuration of body-in-white shops means that every product goes through the same sequence of stations, limiting the ability to produce different body styles on the same system. Manufacturers thus require a new architecture for the body-in-white production line that can handle model diversity and new automobile launches easily and quickly without overinvestment. Second, in final assembly lines, each production plant has to cover different production market segments. This means they need to implement mixed model final assembly lines so that different automobile models can be sequentially personalised on the same final assembly line. This requires the production system of mixed model assembly lines to be reviewed and updated (Kinutani, 1997; Kochan, 2003; Ponticel, 2006).

The benefits of modular product architecture are therefore contingent on manufacturing features and are closely related to the carmaker's ability to effectively use its production capabilities. From a manufacturing approach, three points are crucial. First, regarding economies of scope, these depend on its product portfolio (Goldhar and Jelinek, 1983; MacDuffie *et al*., 1996). An automaker with a larger product range per segment will benefit from greater platform modularity. However, if the product range is small, increasing modularity in order to include more segments for production may be technically complex and may involve an investment that is disproportionate to the economies of scope achieved. Second, economies of scale are a function of production volumes (Hayes and Wheelwright, 1984; Salvador *et al*., 2002). Manufacturers with larger production in terms of the number of units manufactured per model will obtain better results on scale economies if the platform is more modular. While results will be better, even for manufacturers with small production volumes, a thorough cost-benefit analysis must be performed, taking into account the complexity and investment involved in this greater modularity and the economies of scale expected. Third, operational flexibility is a function of the number of plants in which it will be possible to produce the different variants based on the platform. The larger the manufacturing network, the more plants there will be that can produce the different segments that the degree of modularity allows, so flexibility will be greater, and vice versa.

The purpose of these three analytical hypotheses is to expand the discussion on modular platforms based on the product architecture approach (the dominant one in the literature) with an analysis of manufacturing issues. This eclectic approach helps explain automakers' motivations for investing in a Platform 2.0.

3. Research methodology

3.1. Data

Every company takes a slightly different approach to modular platforms because of their differences in terms of structure and R&D. The definition of a modular platform differs from one company to another; the difference between a traditional standard platform and a modular one can hence be a grey area. The criterion used in this research was to consider a modular platform as one that offers sufficient versatility to adapt to a variety of models in different size segments. Based on this criterion, a review of the platforms used by the 20 largest automobile manufacturers in Europe found that most of them had not started to adopt modular platforms. Seven of them, however, were implementing the following modular platforms: the Volkswagen MQB platform, PSA Peugeot-Citroën EMP2 platform, Renault-Nissan CMF platform, Daimler MRA platform, BMW UKL platform, General Motors' D2XX platform and Volvo's SPA platform.

These seven manufacturers produced in Europe in 2012 a total of 14.2 million cars and light commercial vehicles, that is, 73.5% of total European production (OICA, 2012). This leadership in European production can also be observed in production using standard platforms. The Volkswagen PQ35/46, the PSA Peugeot-Citroën PF2 and the Renault X85/B were the top three platforms in millions of units produced in Europe (Sehgal and Gorai, 2012). This characteristic indicates the high concentration within Europe of these manufacturers' production networks —BMW produces 75% of all its vehicles worldwide in Europe, and PSA Peugeot-Citroën 71% (OICA, 2012)— so the development of manufacturing networks using modular platforms is mostly taking place in Europe.

To gather information on these platforms a questionnaire was send to team managers of all seven manufacturers. As the information could belong to more than one department of the manufacturer, we decided to channel the information request via a single interlocutor that each manufacturer identified as being responsible for the development and industrialisation of the new modular platform. The fieldwork was done from October 2013 to March 2014. The questionnaire requested information such as the technical specifications of the platform (variation of dimensions and modules involved), models and segments included, the plants in the manufacturing network and installed/used production capacity. Below is a brief description of each modular platform, and a resume of the key figures for such platforms is given in table 1.

MQB (Modularer Querbaukasten) by Volkswagen: started in 2012 in the plant in Ingolstadt (Germany) manufacturing the Audi A3, and continued with the production of the new Volkswagen Golf in 2013 and 2014. The MQB is being used for four of the Volkswagen brands (VW, Audi, Seat and Skoda) and replaces the standard PQ25, PQ35 and PQ46 platforms, on which the models in segments B, C and D are assembled. The European manufacturing network will comprise 14 plants for the assembly, initially, of 24 different models of these four brands with an annual production capacity of 3.91 million units.

EMP2 (Efficient Modular Platform) by PSA Peugeot-Citroën: began in the plants of Vigo (Spain), with the new Citroën C4 Picasso, and Sochaux (France) with the new Peugeot 308 in 2013. It will support the assembly of 13 different models in segments C and D of the group's two brands, which were previously assembled on the PF2 and PF3 platforms. Once it has been fully adopted, 6 of the group's plants in Europe will assemble on this modular platform, which has a production capacity of 1.87 million units/year.

CMF (Common Module Family) by Renault-Nissan: adopted at the end of 2013 with the production of the new Qashqai in the plant in Sunderland (United Kingdom), and towards the end of 2014 in Renault, beginning with the Espace in the Douai plant (France). The end of adaptation of the manufacturing network is planned for 2020. Initially, 10 models will be assembled on this new platform in Europe by 2016 —two Nissan and eight Renault, rising to 14 models worldwide when adaptation reaches 100%. The implementation of this platform, with multi-make manufacturing on the production lines of the company's European plants, will involve 7 plants with an assembly capacity of 1.48 million vehicles per year.

UKL (Unter Klasse) by BMW: there are two versions of this platform —UKL1 for front-wheel drive models and UKL2 for rear-wheel drive models. 12 Mini and BMW models can be assembled on it. The first model to use this platform was the Mini Hatchback in the plant in Oxford (United Kingdom) in 2014, and other models will gradually be included until the process is complete in the two German plants that are currently producing the BMW series 1 models. The aim is to produce 900,000 vehicles a year on this platform.

MRA (Mercedes Rear-wheel drive Architecture) by Daimler: While the first platform named MFA (Mercedes Front-wheel drive Architecture) developed for this new vehicle architecture allows only one wheelbase so it cannot be considered a modular platform, the new MRA is a modular platform because it allows for different wheelbases and different vehicle widths. Daimler completes this vehicle architecture with what it calls its Modular Strategy, with common modules for the most important components shared by all its models. This strategy brings added benefits to the production process, especially shorter production time and lower production costs. This MRA modular platform will allow assembly of 8 models in segments D, E and F. The plant in Bremen (Germany) started producing the C-Class model with this platform in 2014, and the European manufacturing network using this platform will have an annual capacity of 900,000 vehicles.

D2XX (Delta 2 XX) by General Motors: the D2XX will replace the standard Delta II and Theta II platforms, so on a worldwide level it will be possible to assemble 12 models of different brands (Opel, Chevrolet, Buick, GMC and Cadillac), allowing for production of 2.5 million vehicles a year by 2018. Production on this platform began in late 2014 with the Chevrolet Cruze at the plant in Lordstown (USA), but it only started to be used in Europe in 2015 at the plant in St. Petersburg (Russia). Only 6 models using this platform will be manufactured in Europe, because the others are sold on non-European markets. Estimated annual capacity is about 1 million vehicles.

SPA (Scalable Platform Architecture) by Volvo: the new Volvo XC70 started manufacturing in Europe using the SPA platform in 2015 at the plant in Torslanda (Sweden). With its high modularity, this platform aims to serve as the base for 7 models in the D and E segments and to achieve a production capacity for the network in Europe of 500,000 vehicles a year. Volvo has been investing $11 billion in its new Scalable Platform Architecture over the period 2013 to 2016. This includes the development and implementation of a new engine named Volvo Engine Architecture (VEA).

Table 1. European modular platform networks: Key figures

Manufacturer (platform)	Year of adoption	Technical specifications and degree of modularity	Standard platforms replaced	Segments[(a)]	Number of models	Capacity[(b)]	Number of plants
Volkswagen (MQB)	2012	The platform is made up of three structural modules (3 front and under-body chassis, 5 front floor and 4 rear floor). In addition to track width, variations are possible in all longitudinal dimensions except that from pedals to front axle (front and rear overhangs, and wheelbase).	PQ25 PQ35 PQ46	B, C, D	24	3.91	14
PSA Peugeot-Citroën (EMP2)	2013	The platform is made up of two structural modules (front end and rear unit). The front end is fixed and the rear unit is variable (6 rear units). This configuration allows for several structural dimensions, including 4 track widths and 5 wheelbases and is complemented by two compatible modules (2 cockpits and 2 suspension architectures).	PF2 PF3	C, D	13	1.87	6
Renault-Nissan (CMF)	2013	The platform has two structural modules (front under-body and rear under-body). This platform allows for different structural dimensions, with different configurations made up of 4 compatible modules, as well as the structural modules (3 low front units and 3 low rear units), 2 engine bays and 3 cockpits.	X84/C D	C, D	14	1.48	7
BMW (UKL)	2014	The platform is made up of the following modules: front bulkhead and engine bay, main floor and the rear/wheelhouse section. But variations are not possible in all the modules. From the point of view of structural dimensions, this architecture allows for 3 different wheelbases.	R50 E80	B, C	12	0.90	3
Daimler (MRA)	2014	This approach called MB Vehicle Architecture focuses on the compatibility of the mechanical modules (axles, front and rear suspension, power train, engine and transmission sets). From the point of view of structural dimensions, this architecture allows for different wheelbases and track widths.	RWD Crossover	D, E, F	8	0.90	2
General Motors (D2XX)	2015	The platform is a flexible set of under-body components that includes brakes and suspension. The design is based on common chassis and power train components for different sizes and configurations.	Delta II Theta II	C, D	6	1.00	5
Volvo (SPA)	2015	The SPA is engineered in 5 sections, of which the front overhang, cabin, rear luggage space and rear overhang can vary in size. From a structural perspective, the only fixed section is the engine bay and bulkhead. This allows for variation in all longitudinal dimensions except for pedals to front axle.	D3 EUCD	D, E	7	0.50	2

(a) Segment refers to the European Commission classification of automobiles based on size: mini cars (segment A), small cars (B), medium cars (C), large cars (D), executive cars (E), luxury cars (F), and multi-purpose and sports utility cars (G).
(b) Expressed in millions of units/year.

Source: Drawn up by the authors.

3.2. Variables

From the four network strategic outputs identified in the literature (Shi and Gregory, 1998; Colotla *et al*., 2003; Miltenburg, 2009), this research studies those that are directly associated with network coordination: thriftiness ability and manufacturing mobility. Thriftiness ability gained by scale and scope economies defines the network's efficiency (Shi and Gregory, 1998), while manufacturing mobility, defined as operational flexibility, represents a longer-term capability for network restructuring (Kogut and Kulatilaka, 1994; Buckley and Casson, 1998). In this research, three variables were used, two referring to thriftiness ability (*economies of scope* and *economies of scale)* and one to manufacturing mobility (*operational flexibility).* They were defined as follows:

Economies of scope: Advantages gained by aggregating different products in the global product portfolio (Kogut, 1989), so the more products (car models) that can be produced in the manufacturing network, the greater the economies of scope. The variable is defined as the number of car models produced in the manufacturing network sharing the same platform.

Operational flexibility: The larger the manufacturing network (number of plants), the greater the operational flexibility for coordinating and transferring resources internationally (Lampón *et al*., 2015). The variable is defined as the number of plants in the network sharing the same platform.

Economies of scale: Advantages gained by aggregating production volumes across plants especially derived from the use of common manufacturing resources on a worldwide scale (Garud and Kumaraswamy, 1995; Mikkola and Gassmann, 2003). These production volumes can be expressed as real production (capacity used) or as installed capacity. In this research, the variable is defined as the installed production capacity in the network sharing the same platform in millions of units/year.

The variables identified in the literature that aim to determine the results of the adoption of modular platforms are linked to the technical characteristics of the product (the platform), and to the manufacturers' production issues. Technical characteristics such as modularity are basic when designing a product (Cusumano and Nobeoka, 1992). From the product architecture approach, modularity makes it possible to achieve economies of scale and greater flexibility in facilities and processes (Ulrich, 1995; Cheung, 2002). In this research the variable used was:

Platform modularity: The degree of modularity is understood as the number of basic independent modules making up a product (Gershenson *et al*., 2003; Jose and Tollenaere, 2005). In the case of a standard platform, there is a single module. As the platform is divided into modules, different structural dimensions become possible. In our research this variable is measured as the number of structural dimensions (longitudinal and track width) that can be varied on the modular platform.

Different manufacturers' production issues condition the network strategic outputs and the results of implementing a modular platform. Economies of scope are efficiencies brought by variety, where the product portfolio strategy is the key (Goldhar and Jelinek, 1983). The characteristics of production networks determine operational flexibility (Kogut and Kulatilaka, 1994). Economies of scale refer to the reduction of per-unit costs relating to production volumes. Production volumes determine the design of processes and production facilities (Rasmussen, 2013). Three variables were used in this research, one referring to the product portfolio (*product range)*, one to the production network (*network size)* and the third to *production volumes.* These were defined as follows:

Product range: The number of products in the firm's portfolio or product line (Kotler, 2003), calculated as the average number of car models per segment.

Network size: The number of total plants of the manufacturing network (Lee, 2006).

Production volumes: The number of units produced during a given period (Zijm and Buitenhek, 1996), defined as the average volume of production per segment measured in millions of units per year.

All these variables were based on information obtained from the questionnaire sent to the person responsible for the development and industrialisation of the new modular platform.

3.3. Analysis and discussion of results

order to study the factors behind network strategic outputs, we performed comparative analyses considering both modular platform design and production issues for each manufacturer. In this research there are 7 networks using modular platforms, and 15 using standard platforms that are being replaced by the new modular platforms. Except for the VW modular platform which replaces three standard platforms, the other six each replace two (see table 1). In The effect of implementing modular platforms was calculated by comparing the network strategic outputs of each modular platform with those of the standard platforms being replaced:

Diffeconscope = [*economies of scope* of the modular platform network] – [average value for *economies of scope* of the standard platform networks replaced].

Diffoperflexib = [*operational flexibility* of the modular platform network] – [average value for *operational flexibility* of the standard platform networks replaced].

Diffeconscale = [*economies of scale* of the modular platform network] – [average value for *economies of scale* of the standard platform networks replaced].

Table 2 shows the values of the variables used, for both the determinants and the results of adopting the modular platforms analysed.

Table 2. Data on determinants and results of adopting modular platforms

Manufacturer	Modular platform	Standard platforms replaced	*Platform modularity*	*Product range*	*Network size*	*Production volumes*	*Diffeconscope*	*Diffoperflexib*	*Diffeconscale*
Volkswagen	MQB	PQ25 / PQ35 / PQ46	4	8	22	1.303	16	9.3	2.607
PSA Peugeot-Citroën	EMP2	PF2 / PF3	3	6.3	13	0.843	6.5	3	0.930
Renault-Nissan	CMF	X84/C / D	3	5.6	15	0.790	5	3.5	0.740
BMW	UKL1	R50 / E80	2	5.3	5	0.410	6	1.5	0.450
Daimler	MRA	RWD / Crossover	2	2.7	7	0.420	4	1	0.450
General Motors	D2XX	Delta II / Theta II	3	4.3	9	0.620	4	2	0.415
Volvo	SPA	D3 / EUCD	4	4.5	3	0.250	4.5	1	0.250

The first analysis aimed to determine the influence of platform modularity on networks' strategic outputs. VW's MQB is the most representative example of a highly modular platform (*platform modularity* = 4), which allows for variations in all longitudinal dimensions except that from pedals to front axle (front and rear overhangs, and wheelbase) and track width. This degree of modularity has allowed the manufacturer to use its modular platform for a total of 24 models from three different segments. With the EMP2 platform (*platform modularity* = 3), PSA Peugeot-Citroën can produce all its models from segments C and D. Daimler's MRA focuses on the compatibility of the mechanical modules (axles, front and rear suspension, power train, engine and transmission sets), with different wheelbases and track widths (*platform modularity* = 2). When we compare the network strategic outputs after adopting the modular platform with the standard platforms they have replaced: the MQB (*Diffeconscope* = 16, *Diffoperflexib* = 9.3 and *Diffeconscale* = 2.607), the EMP2 (*Diffeconscope* = 6.5, *Diffoperflexib* = 3 and *Diffeconscale* = 0.930) and the MRA (*Diffeconscope* = 4, *Diffoperflexib* = 1 y *Diffeconscale* = 0.450), we see large differences in each case and that the greater the platform modularity, the better the outputs. So, to give an example referring to the economies of scope and scale obtained, the modularity of the MQB (*platform modularity* = 4) allows 16 models to be manufactured and 2.607 billion units to share generic parts and common manufacturing resources, as opposed to 4 models and 0.45 million units with the MRA platform (*platform modularity* = 2).

We can therefore conclude that the scalability or the degree of modularity of the platform will determine the results of modular platform adoption, with a greater degree of platform modularity leading to greater strategic outputs. This result is in line with the literature, which states that modular architecture helps achieve flexibility in facilities and processes and supports economies of scale and scope on a worldwide scale (Ulrich, 1995; Garud and Kumaraswamy, 1995; Mikkola and Gassmann, 2003). However, our research adopts the product architecture approach to show that, while to date the key parameters for modular architecture have been aspects such as the number of modules or their compatibility, in the case of modularisation of the basic element of the vehicle (its platform), the key parameters are specifically those that allow the platform's structural dimensions to be changed.

The second analysis aimed to study the influence of production issues on the results of platform modularisation by complementing the product architecture approach that predominates in the literature. This was done by comparing the results of modular platforms with the same degree of modularity. In the case of VW's MQB and Volvo's SPA, from a product architecture approach they have the same modular configuration, which allows for changes in track width and all longitudinal dimensions except that from pedals to front axle (*platform modularity* = 4). However, the results of adoption are very different: MQB (*Diffeconscope* = 16, *Diffoperflexib* = 9.3 and *Diffeconscale* = 2.607) and SPA (*Diffeconscope* = 4.5, *Diffoperflexib* = 1 and *Diffeconscale* = 0.250). Such different results can be explained by analysing them from the point of view of production issues. For example, regarding economies of scope —*Diffeconscope*—, while the MQB allows resources to be shared in 16 more models than the standard platforms it replaces, with the SPA this is only possible in 4.5. This difference stems from the number of models that each manufacturer produces per segment —its *product range*. While VW produces an average of 8 models per segment for its four brands (*product range* = 8), Volvo produces 4.5 different models per segment (*product range* = 4.5). In the case of operational flexibility —*Diffoperflexib*, the MQB network includes an average of 9.3 more production plants in comparison with the standard platform networks it replaces, while the SPA network includes only 1 more plant than the standard platform network it replaces. If we compare the size of the manufacturers' production networks, while VW's network size is 22, for Volvo it is 3, so although the modularity of the SPA might allow for similar flexibility in facilities and processes as the MQB, Volvo does not have as many plants in its network as VW so it cannot incorporate the modular platform in a large number of plants in order to gain greater operational flexibility. These differences in outcomes are no minor matter when considering the costs and benefits of investing in modular architecture. Volvo has been investing $11 billion in its SPA over the period 2013 to 2016 for platform design and adoption in its production plants, whereas VW invested about $72 billion in its MQB from 2009 to 2012.

Along the same line and in order to strengthen this second analysis, we compared the EMP2 in PSA Peugeot-Citroën with the CMF in Renault-Nissan and D2XX in General Motors, all of which have a *platform modularity* of 3. The results are given in Table 2, and show differences between EMP2 (*Diffeconscope* = 6.5, *Diffoperflexib* = 3 and *Diffeconscale* = 0.930), CMF (*Diffeconscope* = 5, *Diffoperflexib* = 3.5 and *Diffeconscale* = 0.740) and D2XX (*Diffeconscope* = 4, *Diffoperflexib* = 2 and *Diffeconscale* = 0.415), although the differences are greater between the first two and the third. When determinants are included in the analysis: EMP2 (*product range* = 6.3, *network size* = 13 and *production volumes* = 0.843), CMF (*product range* = 5.6, *network size* = 15 and *production volumes* = 0.790) and D2XX (*product range* = 4.3, *network size* = 9 and *production volumes* = 0.620), the results can be seen to be directly related to these determinants, so that with higher values for *product range, network size and production volumes*, the values for *Diffeconscope*, *Diffoperflexib* and *Diffeconscale* respectively are also higher. To give an example that illustrates this analysis with regard to economies of scale, the 0.243 million more units/year per segment manufactured by PSA Peugeot-Citroën (*production volumes* = 0.843) than by GM (*production volumes* = 0.620) allow common manufacturing resources to be shared among 0.515 million units more with the EMP2 platform (*Diffeconscale* = 0.930) than with the D2XX platform (*Diffeconscale* = 0.415).

These results show to what extent modularity is not the only determinant behind the benefits of adopting such modular platforms. In fact, manufacturers with a greater number of models and large production volumes per segment obtain better economies of scope and scale when a modular platform is adopted than manufacturers with smaller product ranges and small production volumes; also, manufacturers with larger production networks obtain greater operational flexibility than manufacturers whose production networks comprise fewer plants. This result allows us to expand the discussion on modular platforms based on the product architecture approach, the dominant one in the literature (Ulrich, 1995; Gawer and Cusumano, 2002), with an analysis based on the manufacturing networks approach and manufacturing issues.

4. Conclusions

4.1. Theoretical implications

The paper presents a renewed theoretical framework for analysing the design and adoption of modular platforms linking the manufacturing network approach and the traditional product architecture. This new theoretical framework allowed to identify the variation of structural parameters of the platform as a key element in modular platform design, in addition to the traditional number of modules or the degree of module commonality associated with the product architecture approach (Sánchez, 2004; Hölttä and Otto, 2005). Moreover, this new approach has incorporated the network manufacturing outputs and manufacturing issues in the appraisal of the optimal degree of modularity in the platform.

In the automobile industry, the adoption of modular platforms is a new milestone in production, involving extensive changes in product development and the re-design of production facilities and processes. It offers a new standard for obtaining large economies of scale and scope as well as operational flexibility, optimising manufacturing networks on a global level. The benefits of this new modular strategy for network manufacturing outputs depend not only on the design of the platform itself and its modularity —product architecture approach—, but also on the manufacturing issues of each manufacturer. While the degree of platform modularity determines the complexity involved and the investment required for changing production processes and facilities, characteristics relating to the manufacturer's production conditions, such as product range, production volumes and the characteristics of its manufacturing network, also determine the advisability of adopting such a modular platform.

In general, scholars have identified modularity as a panacea (which increases labour division and outsourcing, fosters supplier involvement, diminishes R&D costs, reduces time-to-market, and favours mass-customisation), but tend to forget the real situation of carmakers. The cost of designing a Platform 2.0 is very high and needs to be carefully evaluated. We propose that a specific issue should be studied, namely, the advisability of developing a Platform 2.0 depending on the characteristics of the individual carmaker's production network. The level of modularity that is necessary and financially feasible to obtain benefits on production networks differs from one manufacturer to other. Large manufacturers that have a substantial product portfolio with relatively little differentiation aim for high levels of modularity, while companies with a smaller product range but a wider variety in size will find that their production volumes would be too small and the range of models too narrow for the development of their own modular platform to be cost-effective. Therefore, some manufacturers with a large product portfolio, large production volumes and large production networks who have already adopted this strategy may re-design their current modular platforms. In the short term they may develop and adopt new modular platforms for certain segments in which they are still working with a standard platform, or in the medium term they may include models from new segments on the platform to gain greater modularity

4.2. Managerial implications

Comparative analysis of the adoption of modular platforms among different manufacturers shows that the managers of VW opted for a more thorough change in its design and production standards, with a high degree of modularity in its platform allowing models from three different segments to be assembled on it. VW's modular strategy, with its large product portfolio and large production volumes (3.91 million units/year on the same modular platform), will bring it greater benefits in terms of flexibility and economies of scope and scale than other smaller manufacturers such as BMW, Daimler or Volvo (which produce less than one million units/year). Even so, the managers of those smaller manufacturers have decided to invest in and, in some cases, have developed a modular platform with a similar degree of modularity to that of the VW group.

Following the VW strategy, the responsible for development and industrialisation of modular platforms of the manufacturers with large production networks, large product ranges and production volumes, such as PSA Peugeot-Citroën, Renault-Nissan and General Motors should rethink their strategy. They might consider re-designing their current modular platforms in the medium term, in order to include a new segment. Also, they might design new modular platforms for segments for which they are currently using a standard platform. Specially, it is in the small-size segments (A and B) where manufacturers can benefit most from adopting such modular platforms because of the initial conditions of their production networks, product ranges and production volumes.

4.3. Limitations and future research

Finally, although modular platforms have only recently been adopted and the sample studied represents almost all the automobile production networks using modular platforms, in order to gain a broader view of the impact of this strategy, in the future it would be of interest to expand this study in two directions: other carmakers, and a worldwide perspective.

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