Determinants in the adoption of new automobile modular platforms

What lies behind their success?

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Abstract

Purpose – The purpose of this paper is to analyse the key factors behind the adoption of new automobile modular platforms from the perspectives of product design, manufacturing network and production systems.

Design/methodology/approach – An in-depth and qualitative cross-case analysis of European manufacturing networks was performed based on the modular platforms of seven automobile manufacturers.

Findings – The adoption of modular platforms has changed automobile product architecture helping automobile manufacturers to improve their manufacturing network outputs. The results show that operational flexibility and scope and scale economies at manufacturing network level depend on the platform design – degree of modularity – and the manufacturer's product and manufacturing network conditions. This new product architecture allows for the new production systems to be efficient in terms of flexibility and versatility without overinvestment.

Originality/value – The main contribution to the research literature is the combination of traditional product architecture with the manufacturing network approach to analyse the influence of product design on production systems, especially regarding the adoption of new automobile modular platforms.

Keywords Product design, Automotive industry, Global manufacturing networks

Paper type Research paper

1. Introduction

The influence of product design in production systems is a relevant topic for production research (Fixson, 2005; Jose and Tollenaere, 2005; MacDuffie, 2013; Asadi *et al.*, 2017). Any significant novelty in product architecture is interesting from both an academic and an applied approach. Although modular platforms have been used in different industries (Sánchez, 2004), their recent adoption by automobile manufacturers amounts to a revolution in product architecture in the automobile industry (Buiga, 2012; Lampón *et al.*, 2017).

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

In order to analyse these automobile modular platforms, the conceptual framework of product architecture is appropriate because it is commonly used to study features related to

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product design, where product variety, modularity and platforms are key concepts (Muffatto and Roveda, 2002; Mikkola and Gassmann, 2003). This analysis should include the improvement of production efficiency as the main goal of creating platforms and of modularisation in the automobile industry (Salerno, 2001; MacDuffie, 2013).

In a context in which production is organised through manufacturing networks based on platforms, this production efficiency may be analysed in terms of the optimisation of manufacturing network outputs (Lampón and Cabanelas, 2014; Lampón *et al.*, 2017). The manufacturing network approach is the theoretical framework that allows for the analysis of manufacturing network outputs and their relation with network organisation, specifically configuration and coordination mechanisms (Shi and Gregory, 1998; Rudberg and West, 2008; Feldmann *et al.*, 2009; Cheng *et al.*, 2011; Szwejczewski *et al.*, 2016). Under this approach, scale and scope economies are traditionally considered to be the elements that define network performance, while operational flexibility represents network efficiency in terms of transferring production within the network.

Previous research has covered some aspects of the relationship between product architecture and global operations networks[1] (Fixson, 2005; Lau *et al.*, 2010; Ülkü and Schmidt, 2011; Pashaei and Olhager, 2015, 2017a ,b). These works have focussed on the product architecture typology – integral architecture vs modular architecture – and its impact on various factors that are relevant for decisions on global operations networks. These include supply chain and market factors (number of key supplier sites, supplier capabilities, distance between suppliers and plants, market segments and market size), but also factors linked to the firm's manufacturing networks (key technologies, plant location, and manufacturing flexibility, scale and scope economies at plant level). However, we have been unable to find literature exploring the relation between the key elements of product architecture – product variety, platform and modularity – and manufacturing network outputs. To address this gap, this research studies the extent to which product architecture determines manufacturing network outputs from the perspectives of product design, manufacturing network and production systems. Also, regarding the adoption of the new automobile modular platforms, the paper aims to answer the following research question:

RQ. How does platform modularisation enable manufacturing for different carmakers in their European manufacturing networks?

The article is structured as follows. The first section reviews the automobile modular platform concept and theoretical aspects behind the influence of product architecture and manufacturer's conditions on manufacturing network outputs. The second section studies the adoption of modular platforms in the European production networks of seven automobile manufacturers. 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 and design

The platform concept is not a novelty in the automobile industry. From the 1960s onward, most carmakers tried to achieve 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. There was no dominant platform design and no single definition, either in general (Baldwin and Clark, 2000) 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. Muffatto (1999) considers that the platform means the core framework of the automobile in which the basic element is the under-body, 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. The platform comprises a set of assets shared by a variety of products (Simpson *et al.*, 2006) that are physically compatible in manufacturing processes (Muffatto and Roveda, 2000).

A key milestone in the platform strategy of the sector was the process of reduction and standardisation[2] in the 1990s (Siddique and Rosen, 1998; Whitney, 2004). The consequence of this process was the design of a single standard platform for different models in the same segment[3] (Holweg, 2008). 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 (García *et al.*, 2005). This standardisation focussed on aspects of product development – simplification of engineering and design processes, reduction of costs and development time (Muffatto, 1999; Suk *et al.*, 2007). It also aimed to take advantage of the economies of scale resulting from a greater number of common units per platform, such as savings on the purchase of components (Korth, 2003).

In recent years, platform strategy has been reviewed, and modular platforms have been adopted in the sector (Sehgal and Gorai, 2012). With standard platforms, carmakers could design and produce different models belonging to a single segment – horizontal variety. The aim of modular platforms is to combine horizontal variety with vertical variety (designing and producing different models from different segments) (Buiga, 2012; Schuh *et al.*, 2013). These modular platforms adopt different configurations but start out from a single scalable design made up of compatible modules and allowing structural dimensions to be varied (such as the front and rear overhang, wheelbase and track width). This variation in structural dimensions allows the assembly not only of several models within the same segment (same size) as with classic standard platforms, but also of models from different segments (different sizes) on a single modular platform (Lampón *et al.*, 2017).

2.2 Modular platforms and manufacturing networks

The manufacturing network approach is the framework for analysing the key elements of manufacturing networks. It includes aspects relating to network organisation (configuration and coordination mechanisms), network outputs[4] and network capabilities[5], as well as relations among all these elements (Shi and Gregory, 1998; Colotla *et al.*, 2003; Miltenburg, 2009; Feldmann *et al.*, 2009; Ma *et al.*, 2012; Szwejczewski *et al.*, 2016). This literature points out that network performance depends, among other factors, on how firms organise their production networks; mainly, how the network is configured (e.g. geographical dispersion) and how coordination is established within it (e.g. coordination mechanisms or knowledge transfer mechanisms) (Shi and Gregory, 1998; Rudberg and West, 2008; Cheng *et al.*, 2011; Szwejczewski *et al.*, 2016). Location aspects related to low production costs or new markets are derived from network configuration (dispersion). Scale and scope economies and operational flexibility are mainly derived from coordination. This is because aspects such as operational flexibility to transfer production within the network or the possibility for a larger number of products to share resources depend on coordination among the plants and among the different activities of the value chain within the network.

The manufacturing networks of carmakers are based on platforms, so that each plant assembles models that share the same platform. Platform strategy brings advantages for the globalisation of production processes: the possibility of transferring production between plants, and cost reduction from using resources on a worldwide scale (Wilhelm, 1997; Simpson *et al.*, 2006). However, in the auto industry it has not been possible to fully achieve these advantages. 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. It was only possible to transfer production among plants producing vehicles within the same segment that could thus only share resources among car models belonging to the same segment (Fleischmann *et al.*, 2006). From a manufacturing network perspective, modular platforms bring an opportunity to take up the above advantages (Lampón and Cabanelas, 2014; Lampón *et al.*, 2017). Plants in different segments can share the same modular platform, and new coordination ties among these plants become possible. These lead to greater operational flexibility among plants using a modular platform, and car models from different segments can share the manufacturing network's resources.

2.3 Determinants in the adoption of modular platforms

The product architecture approach focusses on features related to product design (Ulrich, 1995; Fixson, 2005; Ulrich and Eppinger, 2008). Product variety, modularity and platform are the key concepts within this approach (Muffatto and Roveda, 2002; Mikkola and Gassmann, 2003), and the use of platforms becomes the solution for integrating and efficiently developing varied product families (Baldwin and Clark, 2000). Conceptually, the platform is defined as a common structure from which a stream of derivative products can be developed and produced (Meyer and Lehnerd, 1997). The dimensional parameters of the platform determine the product variety because too much commonality in physical product dimensions may limit the possibilities for product differentiation (Sköld and Karlsson, 2007).

According to the product architecture approach, modular platforms combine modularity with the platforms. The modular platform is the result of modularisation of the basic element (platform) on which the final product is to be built (automobile). With this modularisation, the main innovation of modular platforms is variation in the dimensional parameters. 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 (Lampón *et al.*, 2017). Geometric variations in the platform depend on the modularity 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 compatible[6] structural modules: front and under-body chassis, front floor and rear floor (Buiga, 2012).

The literature stresses that modularity can bring flexibility to facilities and processes at production plant level (Ravasi and Stigliani, 2012; Asadi *et al.*, 2017; Pashaei and Olhager, 2017a ,b). The modularisation of automobile platforms can allow carmakers to obtain this flexibility at production plant level. In this sense, the adoption of modular platforms requires changes in two main processes and facilities in assembly plants: body-in-white[7] shops working with a scalable platform, and final assembly lines which are shared by a large number of models (Buiga, 2012; Lampón *et al.*, 2017). 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 (Patchong *et al.*, 2003; Untiedt, 2008). Manufacturers thus require new architecture for the body-in-white production line that can handle model diversity and new automobile launches easily and quickly without overinvestment (Lampón *et al.*, 2017). Second, in final assembly lines, each production plant has to cover models from different segments. This means they need to implement mixed-model final assembly lines so that different car models can be sequentially personalised on the same final assembly line (Fredriksson, 2006; Ponticel, 2006; Boysen *et al.*, 2009). Therefore, at production plant level, the greater degree of modularity in modular platforms involves technical changes, and requires the re-design of the production plant's processes and facilities, but the economies of scope may be greater.

These changes lead to greater efficiency not only at production plant level but also at manufacturing network level. Production mobility among models from different segments is possible among plants belonging to networks using a modular platform. This operational flexibility for transferring production among plants allows the network's manufacturing resources to be shared by a large number of models from different segments. By increasing both the number of models manufactured in the network and the plants among which production can be transferred, resources can be shared among a larger volume of units at manufacturing network level.

The benefits of modularity are contingent on design and manufacturing features and are closely related to the carmaker's ability to effectively use its production capabilities (Takeishi and Fujimoto, 2003). Economies of scope depend on the product portfolio, and economies of scale depend on the production volumes (Salvador *et al.*, 2002; MacDuffie, 2013). A carmaker with a larger product portfolio and larger production in terms of the number of units manufactured will benefit if the platform is more modular. Greater platform modularity makes it possible to aggregate more products (car models) from its extensive product portfolio, and a greater volume of units will be produced in the manufacturing network. Therefore, common manufacturing resources will be shared by a greater number of different models – economies of scope – and by a greater volume of units – economies of scale (Wilhelm, 1997; MacDuffie, 2013). Increasing the modularity of the platform in order to include models from more segments is technically complex from a product architecture perspective and involves important changes in manufacturing process and facilities (Buiga, 2012; Lampón *et al.*, 2017). So, in the case of manufacturers with a small product portfolio and small production volumes, a high degree of platform modularity that allows them to increase the number of models produced and their production volumes will not guarantee a better cost-benefit ratio in view of the investment required and the network outputs obtained.

At the same time, operational flexibility is the ability to shift production among plants in the manufacturing network (Shi and Gregory, 1998). In the automobile sector, this operational flexibility has been used to optimise the network's global capacity (Lampón *et al.*, 2015), or to adapt production to changes in demand in different geographical markets during the product life cycle (Fleischmann *et al.*, 2006; Wittek *et al.*, 2011). It must be stressed that operational flexibility in the sector depends on: the features at production plant level – flexibility and compatibility of processes and facilities, and the factors relating to the network – the number of plants it comprises (Francas *et al.*, 2009; Wittek *et al.*, 2011; Lampón *et al.*, 2015). At production plant level, the literature highlights that product modularity brings flexibility to facilities and processes (Watanabe and Ane, 2004; Pashaei and Olhager, 2017a ,b). The modularity offered by the new platforms therefore makes it possible to achieve flexible production systems and facilities in plants. It is manufacturing network factors that limit the operational flexibility that can be achieved by adopting modular platforms. The larger a carmaker's manufacturing network, the more plants there will be that can produce the different segments allowed by the modularity, so flexibility will be greater as production can be shifted among a greater number of plants (Allen and Pantzalis, 1996; Tong and Reuer, 2007). However, if the carmaker's network is small, say, an extreme case of two plants, then, regardless of the modularity of the platform and the flexibility of the processes, the production of different models can still only be shifted between the two plants.

Table I summarises the theoretical framework adopted in this research, the theoretical approaches and analytical perspectives, and the key concepts, both general and specific to the sector, associated with each of the perspectives. This framework combines the traditional product architecture and manufacturing network approaches to analyse the adoption of the new automobile modular platforms. In each of the perspectives of

Perspectives	Product design	Manufacturing network	Production (plant) systems
Theoretical approaches	Product architecture approach	Manufacturing network approach	
General key concepts	Product architecture Product variety Platform Modularity Modular platform Degree of modularity Compatible modules Manufacturer's (product) conditions Product portfolio	Manufacturing network outputs Economies of scope Economies of scale Operational flexibility Manufacturing network organisation Configuration Coordination Manufacturer's (network) conditions Network size Production volumes	Facilities Processes
Specific automobile key concepts	Car model Car (size) segment Structural compatible modules (front and under-body chassis, front floor and rear floor) Structural dimensions (front and rear overhangs, wheelbase and track width)		Body-in-white shop Final assembly lines

Table I. Theoretical framework for the analysis: perspectives and key concepts

product design, manufacturing network and production systems, key elements covered in the literature that may influence manufacturing network outputs associated with this new automobile architecture are included. In the analysis, the product design perspective includes not only the traditional elements of product architecture – product variety, platform and modularity, but also the manufacturer's product conditions. The manufacturing network perspective includes as key elements for analysis the manufacturer's network conditions and those of the network organisation. Finally, the impact of this new architecture on the re-design of facilities and processes is analysed from the perspective of production systems at plant level.

3. Empirical research

3.1 Methodology and data

Carmakers take a slightly different approach to modular platforms because of their differences in terms of structure. The definition of a modular platform differs from one manufacturer to another; 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 segments in comparison with standard platforms that can only include models of a single segment. Based on this criterion, a review of the platforms used by the 20 largest automobile manufacturers in Europe found that 9 of them had started to adopt modular platforms: BMW, Daimler, Fiat, Ford, General Motors, Renault-Nissan, PSA Peugeot-Citroën, Volkswagen and Volvo.

Since modular platforms are still being implemented in the sector, the information available is limited. Although some manufacturers have published reports, they contain insufficient information for an in-depth study of the phenomenon. Therefore, information on these platforms had to be gathered directly from the manufacturers. A questionnaire was chosen as the method for garnering the data. The questionnaire was sent to each of the nine carmakers. 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 design, development and industrialisation of the modular platform. The fieldwork was done from October 2013 to March 2014. A total of seven manufacturers responded to the questionnaire.

The seven manufacturers who responded were designing and implementing the following modular platforms: the Volkswagen MQB platform, PSA Peugeot-Citroën EMP2 platform, Renault-Nissan Common Module Family (CMF) platform, Daimler MRA platform, BMW UKL platform, General Motors' D2XX platform and Volvo's SPA platform. Using these seven modular platforms, these manufacturers assembled a total of 10.56m cars, that is, 53.4 per cent of total European production in 2017 (OICA, 2017). Considering the high concentration within Europe of these manufacturers' production networks – BMW produces 75 per cent of all its vehicles worldwide in Europe, and PSA Peugeot-Citroën 71 per cent (OICA, 2017) – the adoption of modular platforms is mostly taking place in Europe.

Once the questionnaires had been returned, the methodology used to analyse the data follows a qualitative approach comprising a description of each case study and cross-case study analyses.

3.2 Description of the case studies

The questionnaire data made it possible to describe the key aspects of each of the seven modular platform manufacturing networks.

MQB (Modularer Querbaukasten) by Volkswagen. Volkswagen is the largest carmaker in Europe. Its European network has 22 production plants in nine countries to assemble a large portfolio of products from all segments (an average of eight car models per segment). This manufacturer is also in the lead in terms of production volume, with over 5m units produced per year on the continent (0.755m cars/year per segment). The firm began manufacturing under this modular platform the new generation of Audi A3 in 2012 in the plant in Ingolstadt (Germany).

From the product design perspective, this MQB platform 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). The MQB replaces the standard PQ25, PQ35 and PQ46 platforms. The MQB platform is sufficiently flexible to underpin 24 models of three segments (B, C and D) for four brands (VW, Audi, Seat and Skoda).

From the manufacturing network perspective, this new modular platform makes it possible to produce its segment C and D vehicles in new locations (e.g. Kaluga in Russia), thus coming closer to customers in today's markets. Regarding coordination within the modular platform production network, multi-brand production has been stepped up. While it already existed in standard platform networks, it was limited to certain plants and only some of the brands. This new modular platform has allowed the establishment of new ties and knowledge transfer among plants in different segments. Regarding distribution and coordination among the activities within the network's value chain, one of the plants incorporated the body-in-white process so that all the plants in the network could carry out all the processes (stamping, body-in-white, painting and final assembly). As a result, in terms of manufacturing outputs, the European manufacturing network comprises 14 plants among which production can be transferred and that can assemble 24 different models of the four brands with an annual production of 3.91m units, sharing manufacturing network resources.

EMP2 (efficient modular platform) by PSA Peugeot-Citroën. In terms of the manufacturer's conditions, PSA Peugeot-Citroën in Europe has a total of 13 production plants in seven countries. Its product portfolio includes a wide range of models in segments A to E (an average of 5.4 car models per segment). Its annual production volumes on the continent exceed 2m units (0.445m cars/year per segment). The firm began the production of the Citroën C4 Picasso and Peugeot 308 on the EMP2 platform in 2013 in the plants in Vigo (Spain) and Sochaux (France), respectively.

From the product design perspective, the EMP2 platform is made up of two compatible structural modules: the front end chassis and the rear unit. This architecture allows three structural dimensions to be varied (track width, rear overhang and wheelbase). In addition, the architecture includes two non-structural modules (cockpit and suspension systems). This architecture makes it possible to vary three structural dimensions (track width, rear overhang and wheelbase). This modular platform allows the manufacture of 13 models in segments C and D of the group's different brands (Peugeot, Citroën and DS), 9 models previously developed on the PF2 platform and three on the PF3 platform. The EMP2 also includes the production of the next generation of light commercial vehicles in 2018.

From the manufacturing network perspective, since 2016, the replacement for the Peugeot 5008 (segment C) has been manufactured in the plant in Rennes (France), where previously the standard platform only allowed for the production of segment D vehicles. Production mobility now exists among all the plants in the network. Regarding configuration, there are no differences with regard to the standard platform networks that the modular platform replaced because, initially, no new geographical locations have been included in new segments. However, in the long term and to be closer to the market, the production of light commercial vehicles is planned for Russia. Regarding coordination, the new modular platform network continued with the multi-brand production that already existed in the standard platform networks. Regarding the distribution of the value chain activities; all the plants in the modular platform network include all the processes of a typical assembly plant. This new modular platform has allowed the establishment of new ties and knowledge transfer among plants in different segments. As a result, in terms of manufacturing outputs, a total of 6 of the group's plants in Europe will assemble an annual production of 1.87m units on the EMP2 modular platform. Operational flexibility to transfer production among the 6 plants allows the 13 models to share the network's manufacturing resources (facilities and processes).

Common Module Family (CMF) by Renault-Nissan. The Renault-Nissan alliance has a European network comprising 15 production plants in seven countries. Its product portfolio includes a wide range of models in segments A to F (an average of six car models per segment) and its production volumes exceed 2m vehicles (0.425m cars/year per segment). The CMF platform was adopted at the end of 2013 with the production of the new Qashqai in the plant in Sunderland (UK), and towards the end of 2014 in Renault, beginning with the Espace model in the Douai plant (France).

From the product design perspective, the CMF platform has two compatible structural modules (front under-body and rear under-body). This configuration is complemented by various compatible non-structural modules (engine bay, cockpit and electrical/electronic architecture). This architecture makes it possible to vary three structural dimensions (track width, rear overhang and wheelbase). This modular platform replaces the former X84/C-platform and D-platform. In Europe, it allows 14 models of the two brands in segments C and D to be assembled on it.

From the manufacturing network perspective, in comparison with the standard platform networks the modular platform replaced, initially there were no differences in the configuration. It is of interest that Turkey forms part of the modular platform network. Although initially this plant has not included new segments apart from those made with the former standard platform, in the medium term it might facilitate the production of new car segments in this market. Regarding coordination, the new modular platform network has now started multi-brand production, and although this initiative has not yet been adopted throughout the network, complete adoption is planned. Regarding the distribution of value chain activities in the network, all the plants using the modular platform include the all processes (stamping, body-in-white, painting and final assembly). This new platform has allowed the establishment of new ties and knowledge transfer among plants producing different segments, although this has only just begun between the two different brands. In terms of manufacturing outputs, once the implementation of multi-brand manufacturing has been completed in the European plants, 7 of them will be able to transfer production among each other and assemble 14 different models of the two brands, with a production of 1.48m vehicles per year.

UKL (UnterKlasse) by BMW. BMW possesses five plants in Europe in two countries (Germany and the UK) although it uses contract manufacturers'[8] plants to assemble some of its models. Its product portfolio includes models of the segments B to F (an average of 4.4 car models per segment). Its production volumes are small in comparison with the large European manufacturers, 1m vehicles per year (0.240m cars/year per segment). The UKL platform started with the production of the Mini Hatchback in the plant in Oxford (UK) in 2014.

From the product design perspective, there are two versions of this platform – UKL1 for front-wheel drive models, and UKL2 for rear-wheel drive models. The UKL platform is made up of three compatible modules: front bulkhead and engine bay, main floor and the rear/wheelhouse section. But variations are not possible in all the modules. This architecture allows for variation in two structural dimensions (track width and wheelbase). In Europe, the UKL replaces two standard platforms and allows 12 models of the two brands in segments B and C to be assembled on it.

From the manufacturing network perspective, the European modular platform network comprises three plants, one in the UK and two in Germany. This makes it impossible to change the configuration of the manufacturing network based on this modular platform. Regarding coordination, the company has recently, and for the first time, started multi-brand production but in a contract manufacturer's plant rather than in its own manufacturing network. The modular platform network will maintain the same distribution of value chain activities as standard platform networks because all its plants include all the processes. This new modular platform has allowed the establishment of new ties and multi-brand knowledge transfer in the manufacturing process. In terms of manufacturing outputs, with the implementation of multi-brand manufacturing in their own production network, the three plants would be able to transfer production among each other and assemble 12 different models of the two brands, with a production of 900,000 vehicles a year on this UKL platform.

MRA (Mercedes Rear-wheel drive Architecture) by Daimler. The German manufacturer has five production plants in Europe in three countries. Apart from Germany, it assembles its vehicles in Hungary and France. Its product portfolio covers a wide range of segments, from A to F (Luxury segment), but within each segment it offers just a few models (an average of 2.5 car models per segment), the lowest of all the cases analysed. It produces over 1m vehicles annually in Europe, but the wide range of segments in which it is present means that it produces on average 0.220m cars/year per segment. With this MRA platform, the plant in Bremen (Germany) started producing the C-Class model in 2014.

From the product design perspective, the MRA platform focusses on the compatibility of the seven mechanical modules (axles, front and rear suspension, power train, engine and transmission sets), allowing variation in only two structural dimensions: wheelbase and track width. It was designed for models in the larger-size segments, and allows for the assembly of eight models, replacing two standard platforms.

From the manufacturing network perspective, only two plants in Germany allow production to be transferred between them. As a result, there have been few changes in the organisation of the new modular platform network in comparison with the standard platform. No changes were made in configuration, but in coordination the new modular platform has allowed the establishment of new ties and knowledge transfer between plants producing vehicles in different segments. The modular platform network allows resources to be shared by eight models and reaches an annual production of 900,000 units.

D2XX (Delta 2 XX) by General Motors. General Motors is a large American car manufacturer and most of its production takes place outside Europe. However, it has a marked presence in Europe in terms of network size, models and production volumes. The European network is made up of eight plants in five countries. The European portfolio covers the models in segments B, C and D (an average of four car models per segment). More than 1m vehicles are produced (0.325m of cars/year per segment). The 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.

From the product design perspective, the D2XX platform is a flexible set of under-body components that includes non-structural mechanical modules (power train, brakes and suspension). The design is based on common chassis and power train components for different sizes and configurations. This architecture allows for variation in three structural dimensions (track width and two longitudinal dimensions). 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, Vauxhall and Cadillac), but only 6 models using this platform will be manufactured in Europe.

From the manufacturing network perspective, the European modular platform network comprises 4 plants. Although the configuration of the network allows the production of new car segments in emerging markets, there have been no initiatives in this direction and there is no clear plan for the future. Regarding coordination, the company has started to establish new ties and knowledge transfer among plants producing vehicles in different segments. The modular platform network maintains the same distribution of value chain activities as standard platform networks; all the plants in the network include all the processes. In terms of manufacturing outputs, the five plants will be able to transfer production among them and 1m units of the six different European models will share network resources.

Scalable platform architecture (SPA) by Volvo. This Swedish manufacturer has two production plants, one in Sweden and one in Belgium. It focuses on the production of three segments (C, D and E) and its product portfolio includes 12 models (an average of 4 car models per segment). Annual production on the continent is 600,000 vehicles (0.200m of cars/year per segment). The new Volvo XC70 started manufacturing in Europe using the SPA platform in 2015 at the plant in Torslanda (Sweden).

From the product design perspective, the SPA platform 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 sections are the engine bay and bulkhead. Variations in track width and in all longitudinal dimensions are possible, except for the distance from pedals to front axle (front and rear overhang, and wheelbase). With its modularity, this platform replaces two standard platforms for the assembly of 7 models in the D and E segments.

From the manufacturing network perspective, the European platform network is made up of the company's two plants so there have been practically no changes with regard to the standard platforms in either configuration or coordination within the network. This new modular platform has led to the establishment of new ties between the two plants and knowledge transfer between them, mainly for internal changes in assembly lines for the manufacturing of different segment models. In terms of manufacturing outputs, with implementation of the platform, the two plants will be able to transfer production to each other and assemble seven different models, producing 500,000 vehicles a year.

The following tables summarise the main aspects of the cases analysed. Table II summarises the characteristics of the modular platform from the product design perspective. Table III shows the key aspects of the manufacturing network organisation and the network outputs of each modular platform. Table IV summarises the conditions of each manufacturer in Europe with regard to product portfolio, the size of its manufacturing network and its production volumes.

3.3 Cross-case study analyses

To compare the results of modular platform adoption, four cross-case analyses were carried out. The first aimed to determine the influence of platform modularity on manufacturing network outputs. Three manufacturing networks with different degrees of platform modularity were used for this first analysis. The following three cross-case analyses compared the results of modular platforms with the same degree of modularity. The results of the analyses can be seen in Figures 1–3.

Manufacturer (platform)	Technical specifications and compatible modules	Degree of modularity (variation of structural dimensions)	Standard platforms replaced	Segments
Volkswagen (MQB)	Made up of three compatible structural modules (three front and under-body chassis, five front floor and four rear floor)	Track width Front overhang, rear overhang, wheelbase	PQ25 PQ35 PQ46	B, C, D
PSA Peugeot-Citroën (EMP2)	Made up of two compatible structural modules (front end chassis and rear unit). The front end is fixed and the rear unit is variable (six rear units). Complemented by two compatible non-structural modules (two cockpits and two suspension systems)	Track width Rear overhang, wheelbase	PF2 PF3	C, D
Renault-Nissan (CMF)	Two compatible structural modules (three front under-body and three rear under-body) complemented by compatible non-structural modules (two engine bays, three cockpits and electrical/electronic architecture)	Track width Rear overhang, wheelbase	X84/C D	C, D
BMW (UKL)	Made up of compatible modules: front bulkhead and engine bay, main floor and the rear/wheelhouse section. But variations are not possible in all the modules	Track width Wheelbase	R5 E8 and F2	B, C
Daimler (MRA)	This approach called MB Vehicle Architecture focuses on compatibility of the mechanical modules (axles, front and rear suspension, power train, engine and transmission sets)	Track width Wheelbase	RWD Crossover	na[a]
General Motors (D2XX)	A flexible set of under-body components that includes power train, brakes and suspension. The design is based on common chassis and power train components for different sizes and configurations	Track width Two longitudinal dimensions[a]	Delta II Theta II	C, D
Volvo (SPA)	Engineered in 5 sections, of which the front overhang, cabin, rear luggage space and rear overhang may vary in size. From a structural perspective, the only fixed section is the engine bay and bulkhead	Track width Front overhang, rear overhang, wheelbase	D3 EUCD	D, E

Note: [a]Information not available

Table II. Modular platforms: product design

Manufacturer (platform)	Key aspects of manufacturing network organisation	Manufacturing network outputs: Economies of scope[a]	Economies of scale[b]	Operational flexibility[c]
Volkswagen (MQB)	Configuration changes in new segments: close to market Coordination issues Intensity of multi-brand manufacturing New coordination ties and knowledge transfer between plants of different segments Actions to achieve the same value-added chain distribution in the network	24	3.91	14
PSA Peugeot-Citroën (EMP2)	Configuration changes in new segments (planning of commercial vehicle production in new market) Coordination issues: New coordination ties and knowledge transfer between plants in different segments	13	1.87	6
Renault-Nissan (CMF)	Configuration changes in new segments: close to market (possible in medium term) Coordination issues First initiatives for multi-brand production (not yet reaching the whole network) New coordination ties and knowledge transfer between plants in different segments (start of inter-brand coordination)	14	1.48	7
BMW (UKL)	New coordination ties and knowledge transfer between brands (first experience in contract manufacturer's plant, with plans to spread to the manufacturer's own plant network)	12	0.90	3
Daimler (MRA)	New coordination ties and knowledge transfer between the two plants in different segments	8	0.90	2
General Motors (D2XX)	New coordination ties and knowledge transfer between plants in different segments (first initiative, not reaching the whole network)	6	1.00	5
Volvo (SPA)	Coordination ties and knowledge transfer within the new internal setup of production lines (first initiative to assemble models in different segments on the same lines)	7	0.50	2

Notes: [a]Models that share the manufacturing network resources; [b]production (in millions of units/year) that share the manufacturing network resources; [c]plants that allow for production to be transferred between them

Table III.
Modular platforms: manufacturing networks

Manufacturer	Product portfolio: Segments	Models per segment	Network size: Number of plants	Presence	Production volumes[a]: Total of units	Million units per segment
Volkswagen	All segments	8	22	9 countries	> 5m	0.755
PSA Peugeot-Citroën	From A to E	5.4	13	7 countries	> 2m	0.445
Renault-Nissan	From A to F	6	15	7 countries	> 2m	0.425
BMW	From B to F	4.4	5	2 countries	> 1m	0.240
Daimler	From A to F	2.5	5	3 countries	> 1m	0.220
General Motors	B, C and D	4	8	5 countries	> 1m	0.325
Volvo	C, D and E	4	2	2 countries	> 0.5m	0.200

Note: [a]Per year

Table IV.
Product and manufacturing network conditions of the manufacturers

Comparison between manufacturing networks with different degrees of platform modularity: MQB at Volkswagen, EMP2 at PSA Peugeot-Citroën and MRA at Daimler. Volkswagen's MQB is the most representative example of a high modularity. The MBQ platform is made up of three compatible modules (front and under-body chassis, front floor and rear floor)

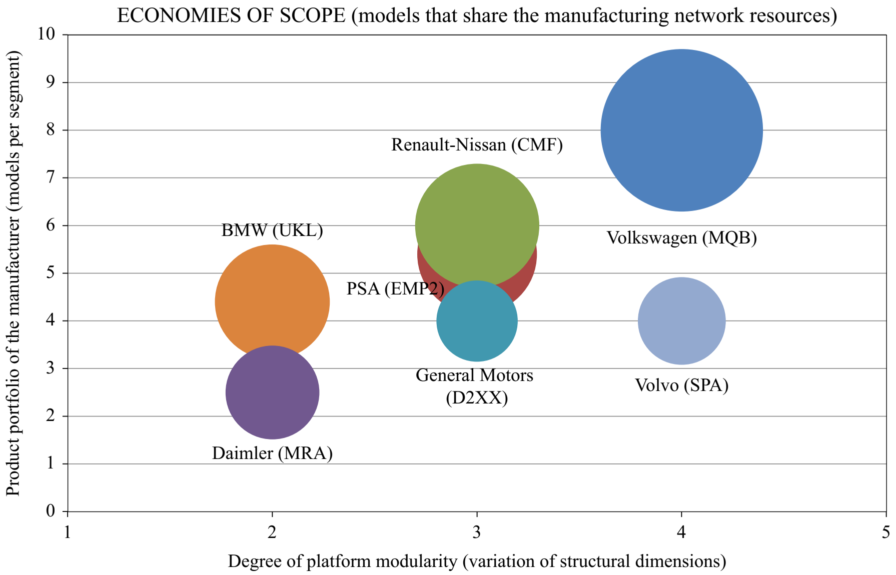

Figure 1.
Economies of scope depending on degree of platform modularity and manufacturer's product portfolio

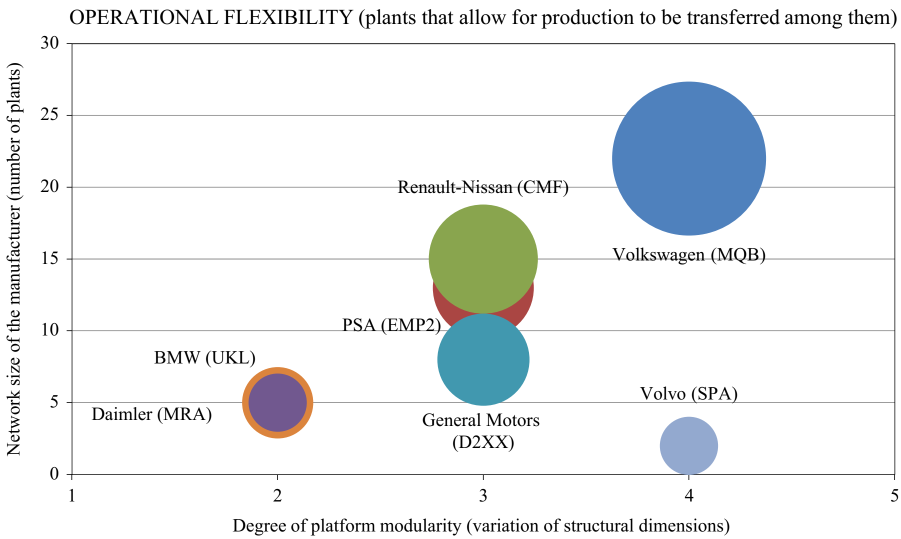

Figure 2.
Operational flexibility according to degree of platform modularity and manufacturer's network size

which allows for variations in four structural dimensions: all longitudinal dimensions except that from pedals to front axle (front and rear overhangs, and wheelbase) and track width. This modularity has allowed a total of 24 models from three different segments to be included. The EMP2 platform at PSA Peugeot-Citroën is made up of two compatible structural modules (front end chassis and rear unit) and two compatible non-structural modules (cockpit and suspension systems) and enables variation of three structural dimensions. PSA Peugeot-Citroën can produce all its models from segments C and D using

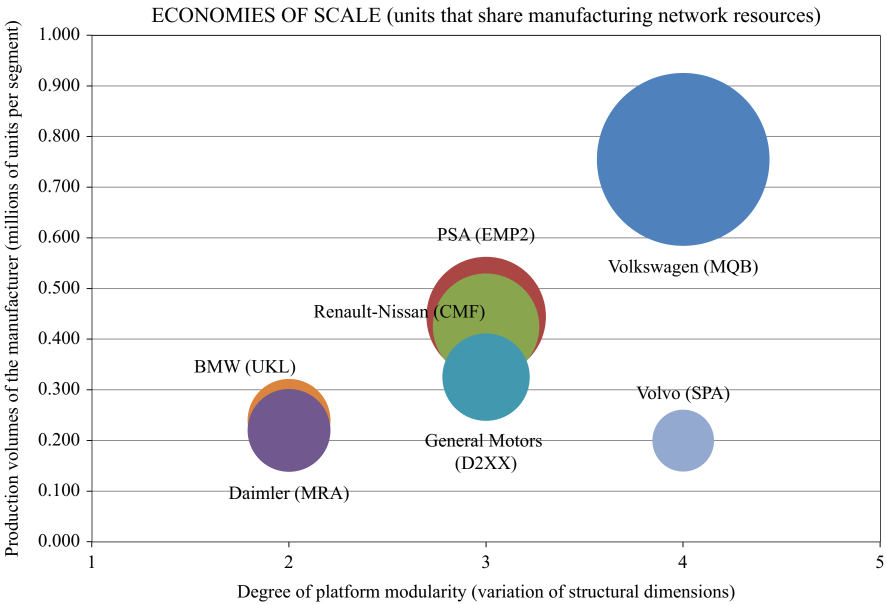

Figure 3.
Economies of scale according to degree of platform modularity and manufacturer's production volumes

this platform. Daimler's MRA focusses on the compatibility of the seven compatible mechanical modules (axles, front and rear suspension, power train, engine and transmission sets), allowing variation of only two structural dimensions: wheelbase and track width. Comparison of these modular platforms indicates that having a greater number of compatible modules does not mean that a greater number of segments can be included, as not all modules allow variation of the structural dimensions of the platform. In fact, the non-structural compatible modules that manufacturers incorporate into the modular design (cockpit, suspension system, transmission sets, etc.) have no impact on variation of the structural dimensions of the platform.

These three manufacturers with differing platform modularity saw different network outputs once the modular platform was adopted. The high modularity of the MQB platform made it possible to integrate three standard platforms and the models and plants that belonged to the networks of these platforms. 3.91m units of 24 models in the B, C and D segments share the resources of a network comprising 15 plants that can transfer production among them. When this network is compared with the EMP2 one, we see that they are both organised in a similar way regarding initiatives in their configuration and coordination, but the EMP2 modularity only allows for two standard platforms to be included as opposed to three for the MQB. The result of this lower degree of modularity means that a smaller number of models (13) and of units (1.87m) share the manufacturing resources, and that the network is made up of a smaller number of plants, only six. Finally, Daimler's MRA platform has a lower degree of modularity allowing variation in only two structural dimensions. This platform, which focusses on improvement of the product design based on the compatibility of the mechanical modules, has lower network outputs in comparison with those obtained with the MBQ and the EMP2. At production network level resources can be shared among nine models, and production mobility is only possible between two plants. This limits the possibility of establishing coordination ties and knowledge transfer among a larger number of plants in different segments and brings lower economies of scale in terms of the units that share the network's manufacturing resources. 900,000 units are produced as opposed to 1.87m with the EMP2 or 3.91m with the MBQ.

Comparison between manufacturing networks with the same degree of platform modularity

(1) Volkswagen's MQB and Volvo's SPA

A clear example of the influence of manufacturer's conditions on the adoption of modular platforms can be seen by comparing Volkswagen's MQB and Volvo's SPA. From the product architecture perspective, these platforms have the same modular design, which allows for changes in track width and all longitudinal dimensions except that from pedals to front axle. Like Volkswagen's MBQ, Volvo's new SPA modular platform has led to marked improvements in aspects of product development, with simpler engineering and design, so that the segments in which the company is developing the greatest variety of vehicles can be included in this new architecture. However, when transferring this new modular design to production in its manufacturing network, Volvo was not able to obtain the same results as Volkswagen in terms of manufacturing network outputs because they were not able to utilise the advantage of the modular platform in their small network. The product portfolio, with fewer models per segment, reduces the possibility of achieving greater economies of scope even though both platforms have the same degree of modularity. But, undoubtedly, the main conditioning factors in the adoption of the new production design are network size and organisational possibilities. Volkswagen production is supported by a network of 22 plants in nine countries that produce more than 5m vehicles in Europe, while Volvo has just two plants in a network that produces less than 1m units in Europe. These differences in network size also affect key aspects of their organisation, such as the possibility for the production of new car segments in markets or for coordination ties to be established among a larger number of plants in different segments.

(2) EMP2 at PSA Peugeot-Citroën, CMF at Renault-Nissan and the D2XX at General Motors

In order to strengthen this analysis, we compared the EMP2 at PSA Peugeot-Citroën with the CMF at Renault-Nissan and the D2XX at General Motors, all of which have the same degree of modularity. The architecture of these platforms allows variation in three structural dimensions (track width and two longitudinal dimensions). The similarities in the architecture allow the modular platforms to replace two standard platforms and to include models from two segments (C and D) in all three cases. The adoption of this similar product design had a different impact on the performance of the production network, which was better for the first two (EMP2 at PSA Peugeot-Citroën and CMF at Renault-Nissan) than for the third (D2XX at General Motors). Regarding scope economies, the product variety per segment in Europe of Renault-Nissan and PSA Peugeot-Citroën, which was greater than that of General Motors, allowed them to share their manufacturing resources among a larger number of different models. The results in terms of operational flexibility and scale economies can be explained in terms of different network size, network organisation and production volumes. PSA Peugeot-Citroën and Renault-Nissan both have an extensive production network spread out through seven countries and assembling more than 2m vehicles in Europe. The adoption of this new modular architecture has allowed them to take actions at organisation level in both network configuration and coordination. These networks allow multi-brand production and the establishment of coordination ties and knowledge transfer between plants producing in different segments. All this has brought operational flexibility, allowing 1.87 and 1.48m units to share manufacturing resources in the cases of PSA Peugeot-Citroën and Renault-Nissan, respectively. Such economies of scale have not been achieved in the case of the D2XX modular platform. Although General Motors has adopted organisational initiatives (e.g. coordination ties and knowledge transfer between plants in different segments), its smaller network and lower production volumes enable only 1m units to share its manufacturing resources, much less than the other two manufacturers.

(3) UKL at BMW and MRA at Daimler

The last cross-case analysis is between the UKL modular platforms at BMW and the MRA at Daimler, which both have the same degree of modularity (allowing variation in two structural dimensions: wheelbase and track width). In this case, not only is the product architecture identical in terms of variation in its structural dimensions, but the two manufacturers also have similar production conditions and, therefore, a similar impact on their production networks. The European production plants of both manufacturers are similar in size, and their modular platform networks are both organised in the same way. The only difference is in the adoption of multi-brand production for BMW. However, the product portfolios of these manufacturers imply that there are differences in their scope economies (see Figure 1). The BMW portfolio comprises a larger number of models per segment for two brands. The Daimler portfolio covers many segments, from A to F, but within each of them it offers just a few models, resulting in 2.5 models per segment. So, 12 models share manufacturing resources in the BMW modular platform network as against 9 in the Daimler modular network.

4. Discussion of results and conclusions

The paper's main contribution to the research literature is the combination of traditional product architecture with the manufacturing network approach to analyse the influence of product design on production systems, especially regarding the adoption of the new automobile modular platforms. This combination allows us to explore the impact of the key elements of product architecture – product variety, platform and modularity – on manufacturing network outputs, which has received little attention in the literature relating product architecture and global operations networks.

4.1 Theoretical issues from a product design perspective

Regarding the platform as an element of the product architecture, the literature stresses that there was no dominant design and no single definition or concept of the platform as a physical element (Ghosh and Morita, 2002; Simpson *et al.*, 2006; Mahmoud-Jouini and Lenfle, 2010). The results obtained indicate this difference in the concept of new modular platforms, both in their number and in the type of compatible modules they include. What all the manufacturers do have in common is that the modular platforms are made up of compatible structural modules which allow them to include models from different segments in their design, but they differ in both the number of these compatible structural modules and the types of non-structural modules they incorporate into the design.

Regarding the other two key elements of product architecture, modularity and product variety, as well as the number of modules and their compatibility as stressed by the literature (Sánchez, 2004; Hölttä and Otto, 2005), the platform's structural parameters are a key element in the design of the new automobile modular platforms. The results of the research indicate that variation in structural dimensions defines the modularity of these modular platforms and determines product variety. In fact, the compatible non-structural modules that some manufacturers incorporate into their modular platform design (e.g. cockpit, suspension system, transmission sets) do not imply variation in structural dimensions so do not allow for the inclusion of car models from different segments.

4.2 Theoretical issues from a manufacturing network perspective

The literature has stated that modular architecture helps achieve flexibility in facilities and processes and supports scope economies at production plant level, and that integral architecture allows very low unit costs to be achieved for high-volume products, which are related to scale economies, also at production plant level (Watanabe and Ane, 2004; Ravasi and Stigliani, 2012; Pashaei and Olhager, 2017a ,b). The results of this research show that platform modularity brings flexibility to production systems at production plant level. What is new is that it also allows for economies of scope and scale at manufacturing network level. Platform modularity eliminates the rigidity, from the point of view of production mobility, that exists in automobile networks using standard platforms. All the modular platform networks analysed have included the production of models in different segments and have allowed the adoption, amongst others, of multi-brand manufacturing, and, especially, new coordination ties and knowledge transfer among plants. This has brought the operational flexibility needed for transferring production among plants producing vehicles in different segments, and manufacturing resources can be shared among a larger volume of units. Therefore, the adoption of modular platforms is a new milestone that offers a new standard for obtaining large economies of scale and scope as well as operational flexibility, optimising manufacturing networks.

To date, the literature has only partially covered some of the manufacturers' conditioning factors and their impact on network organisation: in particular, manufacturers' network configuration and the location of production in low-labour cost countries or new markets. This research, however, includes in the theoretical framework used for analysis the manufacturer's conditions from the product design and manufacturing network perspectives. The result show that manufacturing network outputs depend not only on the design of the platform itself and its modularity, but also on these conditions of each manufacturer. This research points to the benefits that platform modularity has brought to all manufacturers, both large and small. In addition, we have found that these benefits are determined by the product portfolio and the manufacturer's network size. These factors, amongst others, determine key aspects such as the number of car models that can be manufactured in the network or new coordination ties that can be established among plants. All these are key for obtaining larger manufacturing network outputs.

The adoption of modular platforms has also involved a relevant impact on network capabilities. Accessibility to markets, with the production of new car segments, has promoted interaction and learning about customers' needs. Thriftiness ability was obtained by sharing know-how and expertise on the core technologies, engineering and manufacturing among different product lines (car models of different segments). Technical skill mobility among plants of different segments has facilitated the acquisition of valuable knowledge. The sharing of similar production processes and the use of coordination mechanisms have brought benefits in the form of learning opportunities such as internal exchange and benchmarking.

4.3 Managerial implications and application for production systems

The adoption of these modular platforms has changed automobile product architecture. It has led to important changes for production systems, especially the re-design of production facilities and processes. On the one hand, new production systems must adapt or incorporate new facilities and equipment to assemble the structural modules that make up these platforms. Versatility is key in the design of new layouts for the body-in-white facilities to guarantee that platforms with different dimensional configurations can be produced in all the manufacturing network's plants. And this versatility in the different weld/bonding stations and lines in the body-in-white facilities should allow future versions of these modular platforms to be launched easily and quickly. On the other hand, the assembly processes derived from a modular platform must be designed to produce a wide variety of car models from different segments. This means greater complexity in production planning, scheduling and control, and the need to process management tools that guarantee the flexibility required in these new assembly processes.

The adoption of these new platforms requires large investments to adapt plants to the new production systems. The greater the modularity of the platforms, the greater the technical changes and investments needed. When deciding to adopt a modular platform, managers may include manufacturer's conditions in their analyses in order to define the characteristics of the platform design, specially the degree of modularity that allows for production efficiency in terms of flexibility and versatility without overinvestment. This research stresses that the decisions taken by managers about product design (modular platform) should, in addition to the traditional elements of product architecture, include elements relating to the manufacturing network and its determinants. The latter have a relevant influence on the platform design.

4.4 Limitations and future research

The automobile industry is global, producing components, subsystems and complete systems all over the world. The development and adoption of modular platforms will have an effect on the auto-parts industry. In the future, it would be useful to analyse the impact on the components sector and how final adoption will affect the sector as a whole, including both automobile manufacturers and components suppliers. This future line of research will allow for the inclusion of elements not only from manufacturing networks but also from the global operations networks of automobile manufacturers (e.g. supply chain factors such as the number of key supplier sites, supplier capabilities or distance between suppliers and plants) as well as more in-depth exploration of the findings of other recent research work along these lines (see, e.g. Pashaei and Olhager, 2017b).

Notes

1. Global operations networks include, in addition to the firm's manufacturing network, the distribution system and transportation within the network as well as suppliers and markets (Olhager *et al.*, 2015).
2. 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).
3. In this research, "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 others multi-purpose and sports utility cars (O).
4. Network outputs are the elements that define the network performance. In this research, are included the traditional scope and scale economies at manufacturing network level, and operational flexibility as a measure of efficiency for transferring production within the network (Lampón *et al.*, 2017).
5. Network capabilities are defined as the firm's abilities to develop and utilise organisational relationships. These network capabilities can be categorised into accessibility, thriftiness ability, manufacturing mobility and learning ability (Shi and Gregory, 1998). The accessibility to external resources and the thriftiness ability are capabilities that favour the development of a more competitive network. Manufacturing mobility and learning ability represent longer-term capabilities for network restructuring.

6. A compatible module is one that can be assembled on different models and therefore exchanged among them. In this research, various types of compatible modules are considered depending on whether they fit the vehicle structure or not (structural or non-structural) and, within the non-structural types, whether they perform a mechanical function or not (mechanical or non-mechanical):

   (1) A (compatible) structural module is one that determines the structure and dimensions and support to the other elements making up the vehicle (e.g. front and under-body chassis, front floor and rear floor).

   (2) A (compatible) non-structural module is one that does not have the functions described for the structural module. It can be classified as mechanical or non-mechanical:

      - A (compatible non-structural) mechanical module is one that specifically provides one of the vehicle's mechanical functions (such as the engine, transmission, suspension and braking system).

      - A (compatible non-structural) non-mechanical module is one that has no mechanical function. Such modules are generally delivered by suppliers and are designed to facilitate final assembly on the manufacturer's assembly lines. Examples of such modules are the cockpit and seats.

7. A typical automobile assembly plant includes four manufacturing processes: stamping, body-in-white, painting and final assembly. Body-in-white refers to the stage in automobile manufacturing at which a car body's sheet metal components have been welded together and before painting.

8. Contract manufacturing is a form of outsourcing in which one firm produces under the brand of another. Contract manufacturers provide such services to several (even competing) firms based on the customers' designs and specifications (Ciravegna *et al.*, 2013).

References

Allen, L. and Pantzalis, C. (1996), "Valuation of the operating flexibility of multinational operations", *Journal of International Business Studies*, Vol. 27 No. 4, pp. 633-653.

Asadi, N., Jackson, M. and Fundin, A. (2017), "Linking product design to flexibility in an assembly system: a case study", *Journal of Manufacturing Technology Management*, Vol. 28 No. 5, pp. 610-630.

Baldwin, C. and Clark, K. (2000), *Design Rules: The Power of Modularity*, MIT Press, Cambridge.

Becker, C.M. and Zirpoli, F. (2003), "Organizing new product development: knowledge hollowing-out and knowledge integration – the fiat auto case", *International Journal of Operations & Production Management*, Vol. 3 No. 9, pp. 1033-1061.

Boysen, N., Fliedner, M. and Scholl, A. (2009), "Production planning of mixed-model assembly lines: overview and extensions", *Production Planning & Control*, Vol. 20 No. 5, pp. 455-471.

Buiga, A. (2012), "Investigating the role of MQB platform in Volkswagen group's strategy and automobile industry", *International Journal of Academic Research in Business and Social Sciences*, Vol. 2 No. 9, pp. 391-399.

Cheng, Y., Farooq, S. and Johansen, J. (2011), "Manufacturing network evolution: a manufacturing plant perspective", *Journal of Operations and Production Management*, Vol. 31 No. 12, pp. 1311-1331.

Ciravegna, L., Romano, P. and Pilkington, A. (2013), "Outsourcing practices in automotive supply networks: an exploratory study of full service vehicle suppliers", *International Journal of Production Research*, Vol. 51 No. 8, pp. 2478-2490.

Colotla, I., Shi, Y. and Gregory, M. (2003), "Operation and performance of international manufacturing networks", *International Journal of Operations & Production Management*, Vol. 23 No. 10, pp. 1184-1206.

Cusumano, M. and Nobeoka, K. (1998), *Thinking Beyond Lean*, The Free Press, New York, NY.

Feldmann, A., Olhager, J. and Persson, F. (2009), "Designing and managing manufacturing networks a survey of Swedish plants", *Production Planning & Control*, Vol. 20 No. 2, pp. 101-112.

Fixson, S.K. (2005), "Product architecture assessment: a tool to link product, process, and supply chain design decisions", *Journal of Operations Management*, Vol. 23 Nos 3-4, pp. 345-369.

Fleischmann, B., Ferber, S. and Henrich, P. (2006), "Strategic planning of BMW's global production network", *Interfaces*, Vol. 36 No. 3, pp. 194-208.

Francas, D., Kremer, M., Minner, S. and Friese, M. (2009), "Strategic process flexibility under lifecycle demand", *International Journal of Production Economics*, Vol. 121 No. 2, pp. 427-440.

Fredriksson, P. (2006), "Operations and logistics issues in modular assembly processes: cases from the automotive sector", *Journal of Manufacturing Technology Management*, Vol. 17 No. 2, pp. 168-186.

García, J., Lampón, J.F. and Vázquez, X.H. (2005), "El modelo PSA-Vigo: claves de eficiencia productiva y logística en un entorno ajustado", *Economía Industrial*, Vol. 358, pp. 331-338.

Gawer, A. and Cusumano, M. (2002), *Platform Leadership*, Harvard Business School Press, Boston, MA.

Ghosh, A. and Morita, H. (2002), "Differentiated duopoly under vertical relationships with communication costs", Industrial Organization 0207008, EconWPA, available at: http://econwpa.repec.org/eps/io/papers/0207/0207008.pdf (accessed 5 December 2017).

Hölttä, K. and Otto, K. (2005), "Incorporating design effort complexity measures in product architectural design and assessment", *Design Studies*, Vol. 26 No. 5, pp. 445-564.

Holweg, M. (2008), "The evolution of competition in the automotive industry", in Parry, G. and Graves, A. (Eds), *Build To Order: The Road to the 5 Day Car*, Springer, London, pp. 13-34.

Jetin, B. (1999), "The historical evolution of product variety in the auto industry: an international comparative study", in Lung, Y., Chanaron, J.J., Fujimoto, T. and Raff, D. (Eds), *Coping with Variety. Flexible Productive Systems for Product Variety in the Auto Industry*, Ashgate, Aldershot, pp. 111-145.

Jose, A. and Tollenaere, M. (2005), "Modular and platform methods for product family design: literature analysis", *Journal of Intelligent Manufacturing*, Vol. 16 No. 3, pp. 371-390.

Korth, K. (2003), "Platform reductions vs. demands for specialization", *Automotive Design & Production*, Vol. 115 No. 10, pp. 14-16.

Lampón, J.F. and Cabanelas, P. (2014), "La estrategia de plataformas modulares ¿una nueva revolución en la organización de la producción en el sector del automóvil?", *Universia Business Review*, Vol. 42, pp. 14-31.

Lampón, J.F., Cabanelas, P. and González-Benito, J. (2017), "The impact of modular platforms on automobile manufacturing networks", *Production Planning & Control*, Vol. 28 No. 4, pp. 335-348.

Lampón, J.F., Lago-Peñas, S. and González-Benito, J. (2015), "International relocation and production geography in the European automobile components sector: the case of Spain", *International Journal of Production Research*, Vol. 53 No. 5, pp. 1409-1424.

Lau, A.K.W., Yam, R.C.M. and Tang, E.P.Y. (2010), "Supply chain integration and product modularity: an empirical study of product performance for selected Hong Kong manufacturing industries", *International Journal of Operations and Production Management*, Vol. 30 No. 1, pp. 20-56.

Ma, L., Shi, Y. and Zhao, W. (2012), "Habitual domain exploration in inter-firm networks: a framework for understanding network behaviour", *Journal of Manufacturing Technology Management*, Vol. 23 No. 8, pp. 1057-1070.

MacDuffie, J.P. (2013), "Modularity-as-property, modularization-as-process, and modularity-as-frame: lessons from product architecture initiatives in the global automotive industry", *Global Strategy Journal*, Vol. 3 No. 1, pp. 8-40.

Mahmoud-Jouini, S.B. and Lenfle, S. (2010), "Platform re-use lessons from the automotive industry", *International Journal of Operations & Production Management*, Vol. 30 No. 1, pp. 98-124.

Meyer, M.H. and Lehnerd, A.P. (1997), *The Power of Product Platforms*, The Free Press, New York, NY.

Mikkola, J.H. and Gassmann, O. (2003), "Managing modularity of product architectures: toward an integrated theory", *IEEE Transactions on Engineering Management*, Vol. 50 No. 2, pp. 204-218.

Miltenburg, J. (2009), "Setting manufacturing strategy for a company's international manufacturing network", *International Journal of Production Research*, Vol. 47 No. 22, pp. 6179-6203.

Muffatto, M. (1999), "Introducing a platform strategy in product development", *International Journal of Production Economics*, Vols 60-61 No. 3, pp. 145-153.

Muffatto, M. and Roveda, M. (2000), "Developing product platforms: analysis of the development process", *Technovation*, Vol. 20 No. 11, pp. 617-630.

Muffatto, M. and Roveda, M. (2002), "Product architecture and platforms: a conceptual framework", *International Journal of Technology Management*, Vol. 24 No. 1, pp. 1-16.

OICA (2017), *World Motor Vehicle Production*, Organisation Internationale des Constructeurs d'Automobiles, Paris.

Olhager, J., Pashaei, S. and Sternberg, H. (2015), "Design of global production and distribution networks", *International Journal of Physical Distribution and Logistics Management*, Vol. 45 Nos 1-2, pp. 138-158.

Pashaei, S. and Olhager, J. (2015), "Product architecture and supply chain design: a systematic review and research agenda", *Supply Chain Management: An International Journal*, Vol. 20 No. 1, pp. 98-112.

Pashaei, S. and Olhager, J. (2017a), "The impact of global operations on product architecture: an exploratory study", *International Journal of Operations & Production Management*, Vol. 37 No. 10, pp. 1304-1326.

Pashaei, S. and Olhager, J. (2017b), "The impact of product architecture on global operations network design", *Journal of Manufacturing Technology Management*, Vol. 28 No. 3, pp. 353-370.

Patchong, A., Lemoine, T. and Kern, G. (2003), "Improving car body production at PSA Peugeot Citröen", *Interfaces*, Vol. 33 No. 1, pp. 36-49.

Ponticel, P. (2006), "X5 and Z4 share assembly line", *Automotive Engineering International*, Vol. 114 No. 12, pp. 58-60.

Ravasi, D. and Stigliani, I. (2012), "Product design: a review and research agenda for management studies", *International Journal of Management Review*, Vol. 14 No. 4, pp. 464-488.

Rudberg, M. and West, B.M. (2008), "Global operations strategy: coordinating manufacturing networks", *Omega: International Journal of Management Science*, Vol. 36 No. 1, pp. 91-106.

Salerno, M. (2001), "The characteristics and the role of modularity in the automotive business", *International Journal of Automotive Technology and Management*, Vol. 1 No. 1, pp. 92-107.

Salvador, F., Forza, C. and Rungtusanatham, M. (2002), "Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, Vol. 20 No. 5, pp. 549-575.

Sánchez, R. (2004), "Creating modular platforms for strategic flexibility", *Design Management Journal*, Vol. 15 No. 1, pp. 58-67.

Schuh, G., Arnoscht, J., Rudolf, S. and Korthals, K. (2013), "Modular chassis product platform considering variable quantities for an economical electric vehicle production", in Schuh, G., Neugebauer, R. and Uhlman, E. (Eds), *Future Trends in Production Engineering*, Springer, Berlin, pp. 73-82.

Sehgal, B. and Gorai, P. (2012), "Platform strategy will shape future of OEMs", white paper, Evalueserve, available at: https://sandhill.com/wp-content/files_mf/evalueservewhitepaper platformstrategywillshapefutureofoems.pdf (accessed 13 October 2016).

Shi, Y. and Gregory, M. (1998), "International manufacturing networks to develop global competitive capabilities", *Journal of Operations Management*, Vol. 16 Nos 2-3, pp. 195-214.

Siddique, Z. and Rosen, D.W. (1998), "On the applicability of product variety design concepts to automotive platform commonality", *ASME Design Engineering Technical Conferences, DETC/DTM-5661*, *Atlanta, GA*.

Simpson, T., Siddique, Z. and Jianxin, J. (2006), *Product Platform and Product Family Design: Methods and Applications*, Springer, New York, NY.

Sköld, M. and Karlsson, C. (2007), "Multibranded platform development: a corporate strategy with multimanagerial challenges", *Journal of Product and Innovation Management*, Vol. 24 No. 6, pp. 554-566.

Suk, E., de Weck, O., Kim, I.Y. and Chang, D. (2007), "Flexible platform component design under uncertainty", *Journal of Intelligent Manufacturing*, Vol. 18 No. 1, pp. 115-126.

Szwejczewski, M., Sweeney, M.T. and Cousens, A. (2016), "The strategic management of manufacturing networks", *Journal of Manufacturing Technology Management*, Vol. 27 No. 1, pp. 124-149.

Takeishi, A. and Fujimoto, T. (2003), "Modularization in the car industry: interlinked multiple hierarchies of product, production, and suppliers systems", in Prencipe, A., Davies, A. and Hobday, M. (Eds), *The Business of Systems Integration*, Oxford University Press, Oxford, pp. 254-278.

Tong, T.W. and Reuer, J.J. (2007), "Real options in multinational corporations: organizational challenges and risk implications", *Journal of International Business Studies*, Vol. 38 No. 2, pp. 215-230.

Ülkü, S. and Schmidt, G.M. (2011), "Matching product architecture and supply chain configuration", *Production and Operations Management*, Vol. 20 No. 1, pp. 16-31.

Ulrich, K. (1995), "The role of product architecture in the manufacturing firm", *Journal of Research Policy*, Vol. 24 No. 3, pp. 419-441.

Ulrich, K. and Eppinger, S.D. (2008), *Product Design and Development*, MacGraw-Hill, New York, NY.

Untiedt, A. (2008), "The modular body", in Parry, G. and Graves, A. (Eds), *Build to Order: The Road to the 5 Day Car*, Springer, London, pp. 109-132.

Watanabe, C. and Ane, B.K. (2004), "Constructing a virtuous cycle of manufacturing agility: concurrent roles of modularity in improving agility and reducing lead time", *Technovation*, Vol. 24 No. 7, pp. 573-583.

Whitney, D.E. (2004), *Mechanical Assemblies – Their Design, Manufacture, and Role in Product Development*, Oxford University Press, New York, NY.

Wilhelm, B. (1997), "Platform and modular concept at Volkswagen – their effect on the assembly process", in Shimokawa, K., Jurgens, U. and Fujimoto, T. (Eds), *Transforming Auto Assembly*, Springer, Berlin, pp. 146-156.

Wittek, K., Volling, T., Spengler, T.S. and Gundlach, F-W. (2011), "Tactical planning in flexible production networks in the automotive industry", in Hu, B., Morasch, K., Pickl, S. and Siegle, M. (Eds), *Operations Research Proceedings 2010 (GOR-Gesellschaft für Operations Research)*, Springer, Berlin, pp. 429-434.

Further reading

Gershenson, J.K., Prasad, G.J. and Zhang, Y. (2003), "Product modularity: definitions and benefits", *Journal of Engineering Design*, Vol. 14 No. 3, pp. 295-313.

Jacobs, M., Vickery, S.K. and Droge, C. (2007), "The effects of product modularity on competitive performance: do integration strategies mediate the relationships?", *International Journal of Operations & Production Management*, Vol. 27 No. 10, pp. 1046-1068.

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