Efficiency in design and production to achieve sustainable development challenges in the automobile industry: Modular electric vehicle platforms

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Abstract

Electric vehicles have been based on a new product architecture: modular electric vehicle platforms (MEVPs). Through a case study, this paper uses efficiency and sustainability criteria to analyse this modular architecture as implemented by three automobile manufacturers in their European production networks. The results show that MEVPs have been adopted to achieve the efficiency of mass-production electric vehicles in order to comply with regulatory environmental requirements. MEVPs are designed with structural compatible modules, an electric drive system architecture and modular batteries that can be adapted to each vehicle. These designs are focused on limiting energy consumption by reducing weight with the use of high-performance materials or extra-thin batteries. Some of these MEVPs use fewer components in their design to facilitate disassembly and recycling. This new modular architecture has been implemented through compatible, flexible production systems accompanied by different sustainable production initiatives. The production system has incorporated carbon-neutral production processes or circular economy production models, which include remanufacturing and reuse. Networks resulting from these new MEVPs are geographically concentrated and are not conditioned by location factors. The roles of the plants have been mainly driven by economies of scale to achieve high-performance specialised products and high volumes. These plants play a role as hubs for electric vehicle production in the manufacturers' European production networks.

KEYWORDS
electric vehicles, production networks, sustainable development, sustainable product design, sustainable production processes

1 | INTRODUCTION

Stakeholder pressure and the need to comply with legislation are forcing the automobile industry to design and manufacture fuel-efficient, low-impact, environmentally responsible and sustainable vehicles (Jasiński et al., 2021; Szász et al., 2021). Road transport (goods and passengers) accounts for approximately one-fifth of EU emissions. Cars are the main pollutant, accounting for 60.6% of total European road transport CO₂ emissions (EPRS, 2020). In the US, the transportation sector is one of the largest contributors to anthropogenic greenhouse gas (GHG) emissions. According to the national inventory that the US prepares annually under the United Nations Framework
Constitution on Climate Change, transportation accounted for the largest portion (27%) of total US GHG emissions in 2020, and cars account for 57% of total transportation (EPA, 2022).

As an example, the urgency for climate change mitigation led to a ratclif-ting-up of legal CO2 emission limits for passenger cars by the European Commission (European Parliament and the Council of the European Union, 2019). Competitiveness in the automobile industry involves designing sustainability strategies to ensure compliance with these policies on environmental issues (Gu et al., 2021; Jiang et al., 2018). The incorporation of alternative powertrains, particularly for battery-powered electric vehicles, has been one of the main strategies for complying with these regulations (Gunther et al., 2015). This strategy has been accompanied by important changes related to the vehicles' product architecture.

The solution to respond to the efficiency challenges in product architecture has been modular platforms (MPs) (Lampón et al., 2019; Lampón & Rivo-López, 2021). Under the product architecture approach, the design of these MPs has combined the advantages of modularity with those of platforms (Mikkola & Gassmann, 2003). The scalable design of MPs allows the structural dimensions of this basic element of the automobile to be varied. Thus, several automobile models from different segments (different sizes) can be incorporated on a single MP (Buiga, 2012; Schuh et al., 2013). In terms of production systems, the modularity offered by MPs makes it possible to include flexible production systems and to reorganise facilities so that their specificity can be changed (Lampón, Cabanelas, & González-Benito, 2017). Moreover, MPs have allowed automobile manufacturers to obtain efficiency in production networks. With MPs, production flexibility is possible among plants that produce automobile models from different segments and implies that the network’s manufacturing resources can be shared by a large number of automobile models and by a larger volume of units (Lampón & Cabanelas, 2014; Lampón, Cabanelas, & González-Benito, 2017). In summary, modular product architecture has had an impact on performance in terms of product variety and design costs (Gauss et al., 2020; Stadtherr & Wouters, 2021), manufacturing flexibility (Pashaei & Olhager, 2019) and network outputs (Lampón et al., 2019; Lampón & Rivo-López, 2021).

Despite the interesting findings of these previous works on the impact of modular product architecture and in particular of MPs, their analyses have not included sustainability criteria. Modular product architecture has recently gained special attention in sustainable product design and in sustainable production processes (Ma & Kremer, 2016). In the automobile industry, some of the key aspects in this sustainable context have been the development and production of electric vehicles, reduction of environmental impact over the product’s lifetime, and ensuring reactivity to respond to changes in regulatory requirements (Go et al., 2015; Schöggel et al., 2017). In terms of product architecture, the sustainability challenges in this industry have been accompanied by the development of new modular electric vehicle platforms (MEVPs). These MEVPs are an important innovation in modular vehicle architecture because they include not only the traditional structural modules of the MPs in their design (e.g., under-body) (Lampón, Cabanelas, & González-Benito, 2017; Schuh et al., 2013), but also new elements (e.g., batteries, electric drive system) (Nicoletti et al., 2020). The adoption of these new MEVPs also implies significant changes in production systems and production networks.

This research contributes to the identification of the main features regarding product design, production systems, production networks and sustainable development derived from the adoption of MEVPs to meet the demanding challenges of sustainability that automobile manufacturers are facing.

In order to study how MEVPs are implemented based on efficiency and sustainability criteria, the paper is structured as follows. The first section reviews the modular product architecture and its impact on product design, production systems and production networks. The second section presents a case study of the implementation of MEVPs in the European production networks of three automobile manufacturers. The last section presents the conclusions and proposes future lines for research.

2  |  LITERATURE REVIEW

2.1  |  MEVPs and product design

The product architecture approach focuses on features related to product design in which product variety, modularity and the platform are the key elements (Mikkola & Gassmann, 2003; Shamsuzzoha & Helob, 2017). The platform is defined as a common structure from which a stream of derivative products can be developed (Simpson et al., 2014). The automobile platform is the core framework of the vehicle in which the basic element is the under-body (Lundbäck & Karlsson, 2005; Muffatto & Roveda, 2000), although other components have been included such as axles or the suspensions train (Muffatto & Roveda, 2000).

From the product architecture perspective, MPs combine the platform with the advantages of modularity. The advantage of modularity in the automobile industry is that it offers greater levels of customisation in a high-volume context, efficiency in terms of product variety, module sharing, and improvements in operational aspects of design (Gauss et al., 2020; Piran et al., 2020). Among other factors, the dimensional parameters of the platform determine product variety because an excess of commonality in physical product dimensions may limit the possibilities for product differentiation (Sköld & Karlsson, 2007). MPs adopt different configurations from a scalable design that is made up of compatible modules and allows structural dimensions to be varied (Lampón et al., 2019; Lampón, Cabanelas, & Carballo-Cruz, 2017; Lampón, Cabanelas, & González-Benito, 2017). This design allows several automobile models from different segments to be incorporated on a single MP (Buiga, 2012; Schuh et al., 2013).

In recent years, automobile manufacturers have been developing new MEVPs to produce electric vehicles (Krings & Monissen, 2020). In terms of product architecture, the design of the MEVPs includes new elements, particularly the batteries and the electric drive system, and has different design requirements to the MPs (Nicoletti et al., 2020).
et al., 2020). The design efficiency of MEVPs is mainly related to the architecture and layout of these new elements that comprise it. In terms of product variety, MEVP design offers more than the variety offered by MPs (models from different segments) as it must also allow variety in the power and autonomy of the different models. (Nicoletti et al., 2021). Autonomy is closely related to the capacity and architecture of the batteries, which are tailored to the type of vehicle. In order to look in depth at MEVP design, the following research question is posed:

RQ1. What are the main product design features of the MEVPs related to the product variety, modularity and platform?

2.2 | MEVPs and production systems

There is a link between modular product architecture and the performance of production systems. The literature demonstrates a straight relationship between greater modularity and the ease of assembling a large variety of products (Fixson, 2007; Pashaei & Olhager, 2017; Watanabe & Ane, 2004). Modularity allows the reconfiguration and performance of production systems, especially the flexibility and compatibility of processes and facilities (Francas et al., 2009; Huang et al., 2005). In automobile assembly plants, body-in-white assembly processes are particularly important as they create the vehicle platform and bodywork. Modularity of MPs allows a modular design of the body-in-white assembly process so that different models can share the same flexible line configured through the different sequences of welding stations (Lampón, Cabanelas, & González-Benito, 2017). In the final assembly process, flexibility has been achieved through the implementation of so-called mixed-model assembly lines. These lines allow the assembly of the different models and ensure fast and flexible changes in the sequence of models (Ponticel, 2006; Zeltzer et al., 2017).

Production systems for new MEVPs must have the efficiency required for the mass production of electric vehicles (Krings & Monissen, 2020). In 2030, 30% of all vehicles worldwide are predicted to be electric (Rietmann et al., 2020), although the final percentage will depend on how society takes up new trends in mobility (e.g., Mobility-as-a-Service or Peak Car) (Turienzo et al., 2022). Elements such as the flexibility of production processes are key to producing these high volumes of different products (Asadi et al., 2017). Moreover, production systems adopting MEVPs will have to be able to launch new electric models quickly (Hertzke, 2019). This implies versatile facilities that can be updated or modified for model launches and avoid large investments (Omar, 2011). A study of the production systems in MEVP adoption is therefore required and the following research question is posed:

RQ2. What are the main production systems features of MEVPs related to compatibility and flexibility?

2.3 | MEVPs and production networks

The production network approach is the framework for analysing the key elements of production networks: configuration, coordination mechanisms, the role played by each plant, and network outputs (Cheng & Farooq, 2018; Christodoulou et al., 2019; Miltenburg, 2009; Shi & Gregory, 1998). The production networks of automobile manufacturers are based on platforms where the plants assemble the automobile models that share the same platform (Frigant & Zumpe, 2017). In this production context, carmakers have been using operational flexibility to transfer production between plants to optimise the network’s capacity (Lampón et al., 2015; Lampón, Cabanelas, & Carballo-Cruz, 2017), or to adapt production to changes in demand in different geographical markets (MacDuffie, 2013; Wittek et al., 2011). MPs have brought advantages for production networks in terms of optimisation of production capacity and cost reductions from using resources on a worldwide scale. With MPs, production mobility is possible among plants that produce automobile models from different segments and the network’s manufacturing resources can be shared by many automobile models and by a larger volume of units (Lampón & Cabanelas, 2014; Lampón, Cabanelas, & González-Benito, 2017). The relationship between modular product architecture in general, and MPs in particular, and production network features was established in previous literature. Modular product architecture is related to geographically dispersed production networks to exploit comparative location advantages and the establishment of intensive coordination mechanisms among production plants (Lampón et al., 2019; Pashaei & Olhager, 2019). Plant roles are assigned by location and plant focus criteria, mainly focusing on economies of scope (Feldmann & Olhager, 2019).

Automobile manufacturers must select the plants in their production networks where electric vehicles will be assembled using MEVPs. Assembly of the new elements (e.g., batteries, electric drive system) that MEVPs incorporate (Nicoletti et al., 2020) involves changes in those production plants. The automobile manufacturers must decide whether to integrate electric vehicle production by adapting existing facilities and processes at the plants (Herrmann et al., 2012) or completely transform the plants with specific facilities and processes to produce the electric vehicles (Luccarelli et al., 2013). This decision conditions which plants make up the electric vehicle production network and can be taken on the basis of location criteria (e.g., technological factors) (Pavlínek, 2020) or on plant focus (e.g., focus on economies of scope to assemble all the different models) (Lampón & Rivo-López, 2021). Moreover, these decisions involve other aspects such as the geographic dispersion of the production network and the intensity of the coordination mechanisms among the plants in the network. In order to analyse the production networks derived from MEVP adoption, the following research question is posed:

RQ3. What are the main production network features in terms of configuration, coordination mechanisms and plant roles resulting from the adoption of MEVPs?
2.4 | MEVPs and sustainable development

Electric vehicles as part of sustainable transportation are at the heart of the United Nation’s Sustainable Development Goals (SDGs). They are directly linked to many SDGs including SDG3 (good health and well-being), SDG7 (clean energy), SDG13 (climate), and SDG12 (sustainable production and consumption) (Onat et al., 2021). Moreover, production of electric vehicles has been one of the main initiatives of automobile manufacturers for complying with a sustainable development strategy (Gunther et al., 2015). From this perspective, the implementation of MEVPs is decisive in order to achieve these sustainable development goals.

In terms of sustainability criteria, the reduction of environmental impact and ensuring reactivity to respond to changes in regulatory requirements are key in the automobile industry (Schöggl et al., 2017). The industry has achieved compliance with environmental regulations thanks, in the main, to mass production of electric vehicles. (Jasiński et al., 2021; Krings & Monissen, 2020). In this context, these vehicles need to be based on a modular platform design that allows different models to be manufactured on the same platform. MEVP design, and that of the production systems that will adopt them, must allow the electric vehicles to be produced efficiently.

Sustainable product design includes different relevant aspects (Keitsch, 2012), and what is key in the case of the automobile industry is the reduction of environmental impact over the product’s lifetime (Schöggl et al., 2017). Among other things, practices aimed at such sustainable design in the industry include product design for be recycling or reusing at the end of its lifecycle; use of materials with less environmental impact or use of fewer materials overall in the design (Staniszewska et al., 2020). All these aspects must be taken into account when designing MEVPs in this context.

As far as production processes are concerned, MEVPs can manufacture by using traditional sustainability initiatives such as using fewer resources during the production process or producing less...
pollution and waste. However, in recent works on the automobile industry, researchers have focused on designing production processes that facilitate reuse and recycling, particularly in processes linked to battery production and assembly (Fujita et al., 2021; Pagliaro & Meneguzzo, 2019). Therefore, bearing sustainability criteria in mind, the final research question is posed:

RQ4. How does the adoption of MEVPs contribute to the sustainable development strategy?

As a summary, the framework of this research is presented in Figure 1. It includes the traditional efficiency criteria and the main features of MP adoption pointed out by the literature. The sustainability criteria are added in this framework and the research questions are introduced to identify the main features related to product design, production system, production network and sustainable development resulting from the adoption of the new MEVPs.

3 | METHODOLOGY AND DATA

To respond to the objective of this research, the empirical work was qualitative in its approach and used the case study as a research methodology. Qualitative research allows a rich description and full comprehension, exploration and understanding of a phenomenon (Yin, 2014). One of the methods that serve the purpose of qualitative research is the case study. Case studies allow the analysis of real-life events and an in-depth and detailed examination of either a specific case or a small number of cases (Creswell, 2014). This empirical work consisted of a case study of three automobile manufacturers.

A questionnaire was used to gather the primary data about the adoption of these MEVPs. This questionnaire was built based on the literature review. The information covered is detailed in the Appendix. It comprises four parts: Block (1) the sustainability strategy; Block (2) the elements related to the product design; Block (3) the elements related to the production system; and Block (4) the aspects related to the production network. Block (1) contains the information regarding the general sustainability strategy that provides the framework for MEVP adoption. Sustainable development goals (e.g., environmental impact) and sustainable development initiatives (e.g., sustainable production processes) are included in the questionnaire (Jasinski et al., 2021). Block (2) relates to product design: platform, modularity and product variety are the key elements in the questionnaire. For the platform, the design elements included are the electric drive system architecture and features of the batteries (Chan, 2002; Ehsani et al., 2007). The product variety in this research refers to different automobile models classified based on sizes (segments) (MacDuffie, 2013) and of type of motorisation (hybrid or electric) (Pistola, 2010). Regarding modularity, two aspects were included. First, the number of modules and their compatibility (Sánchez, 2004). In this study, a compatible module is one that can be shared and exchanged among different automobile models; it is defined as a compatible structural module when it also determines the structure and support for the other components making up the vehicle (Lampón et al., 2019). Second, the questionnaire includes the variation of the structural dimensions involved in the platform design (Simpson et al., 2014). In Block (3), the compatible and flexible production system is included in the questionnaire. This includes the standardisation of production processes and implementation of versatile facilities (Lampón, Cabanelas, & González-Benito, 2017).

In Block (4), configuration, coordination mechanisms, plant roles and network outputs are the elements included in the questionnaire. The production network configuration is examined in terms of geographical dispersion (Miltenburg, 2009), defined as the number and location of production plants involved in MEVP adoption. The coordination mechanism incorporated in the questionnaire was knowledge transfer among production plants (Shi & Gregory, 1998). Regarding plant roles, the questionnaire includes the traditional location factors and plant focus to study how roles are assigned (Feldmann & Olhager, 2019). Finally, network outputs include the scope and scale economies, measured by the number of models and production volume that can be shared on the production network (Wilhelm, 1997), and operational flexibility, measured by the number of plants that allow production to be transferred between them (Lampón, 2020; Lampón et al., 2015).

A process of validation of the questionnaire (Forza, 2002) was carried out. This validation was done by means of a pilot test with one of the manufacturers. A first version of the questionnaire was emailed together with instructions for filling it out to the head of design and implementation of the MEVP. Additionally, a conference call was arranged to provide support from the research team in filling out the questionnaire. The pilot checked the validity and understanding of the elements comprising the questionnaire tested, and verified the procedure for receiving, completing and returning it.

To collect the data, the validated questionnaire was sent to the three carmakers. The fieldwork was done from October 2019 to January 2020. The emailed questionnaire also included the instructions for filling it out. As the information could belong to more than one department of the manufacturer, it was decided to channel the information request via a single interlocutor whom each manufacturer identified as being responsible for the development and industrialisation of the modular electric vehicle platform. Respondents were given time to collect data, complete the form and email it back. Later, there was a chance to review the data jointly during a conference call with the research team before finalising data collection.

To preserve confidentiality, the modular electric vehicle platforms implemented by the three automobile manufacturers were called MEVP1, MEVP2 and MEVP3. These three manufacturers have a high concentration of production in their European production networks. Manufacturer1 produces 72.2% of its worldwide production in Europe; for Manufacturer2 the figure is 62.7% and for Manufacturer3, 46.7% (OICA, 2017). In terms of sustainable development, Manufacturer1 is mainly focused on SDG13 (climate), the fight against climate change, reaching carbon net zero emissions by 2038, and on SDG12 (sustainable production and consumption), using natural resources and reduced environmental impacts, contributing to development of local activities in new territories through responsible purchasing
practices. Manufacturer 2 has opted for the elimination of its carbon footprint (SDG13), reducing CO2 emissions throughout the life cycle of vehicles with the aim of reaching carbon neutrality by 2050. Moreover, Manufacturer 2 is mainly committed to SDG11 (sustainable cities and communities) and aims, by 2030, to provide access to safe, affordable, accessible and sustainable transport systems for all. Manufacturer 3 is also mainly focused on SDG13, pledging an investment of 14 billion euros in decarbonisation by 2025, and on SDG7 (clean energy), with the objective of substantially increasing the share of renewable energy in the global energy mix by 2030.

Once the information was collected, a descriptive analysis of each of the three cases was carried out. The information analysed was organised based on the blocks contained in the questionnaire.

## 4 | CASE STUDY ANALYSIS

### 4.1 | Platform MEVP1

#### 4.1.1 | Sustainable development

With the sustainable development strategy, 100% of the manufacturer’s range will be electrified by 2025 (in three different modular electric vehicle platforms). The manufacturer foresees the production of 40 hybrid and electric models in 2025. This strategy started in 2019 with the production of vehicles under MEVP1 across the manufacturer’s brands.

In terms of sustainability, MEVP1 has focused on sustainable product design. The platform has been designed and optimised to limit CO2 emissions by leveraging all of the factors that contribute to lower consumption, especially weight reduction using high-performance materials such as advanced and ultrahigh-strength steel, aluminium and composites. The weight lost by substituting the previous modular platform with MEVP1 is 70 kg. This aspect is of great importance for the platform, as MEVP1 will house hybrid vehicles with two motors (electric and internal combustion). The vehicle’s lower weight will reduce consumption and CO2 emissions in non-electric driving. Moreover, the design of MEVP1 includes fewer components than the substituted MP1. The aim of having fewer parts is to facilitate disassembly at the end of the vehicle’s useful life.

#### 4.1.2 | Product design

MEVP1 is a multi-energy platform, which is designed for electric and hybrid vehicles. MEVP1 is a variant of the MP for internal combustion engine vehicles from the manufacturer. The platform is made up of compatible structural modules (the front-end chassis and the rear unit). This architecture makes it possible to vary structural dimensions (track width, rear overhang and wheelbase). The modular product architecture of the specific elements related to electric vehicles is a skateboard design (batteries in the floor and electric motors in the axles). The battery is located on the rear part of the platform floor. The drive system consists of an electric motor integrated in the rear or front axle, and a combustion motor in the front part of the vehicle. MEVP1 allows the manufacturer to have a product variety of nine vehicle models (year 2022) in the two motorisation versions (electric and hybrid) in the firm’s B and C segments.

### 4.2 | Platform MEVP2

#### 4.2.1 | Sustainable development

The objective of the general sustainable development strategy is to achieve carbon neutrality in 2050. The MEVP strategy of the carmaker is not to develop higher capacity batteries, but will focus on achieving the best balance between cost and range through economies of scale. This strategy started in 2020 with the production of vehicles under MEVP2 across all the carmaker’s brands.

The whole architecture is created to improve energy consumption and aerodynamics, using lightweight materials to lower the overall...
weight. Moreover, the modular design of the batteries is linked to their thickness as they are extra-thin, which allows them to be horizontally and vertically modular (the batteries can be used as stackable modules).

The launch of vehicle production using new modular electric vehicle architecture is accompanied by the first initiative for a circular economy plant. The implementation of this circular economy production model started in 2021 at this production plant, replacing its production of new vehicles. The circular economy production model implemented is based on a set of elements (maintenance, remanufacturing and recycling), aimed at reusing different vehicle components. This pilot plant has a line installed for dismantling end-of-life vehicles. This new facility recovers different parts and materials as well as the batteries. With this production model, the carmaker is aiming for the plant to achieve a negative carbon balance by 2030.

4.2.2 | Product design

MEVP2 is a new platform designed specifically for electric vehicles. The platform has different compatible structural modules that allow variations in track width and longitudinal dimensions. The modular product architecture of the specific elements related to electric vehicles is a skate-board design. MEVP2 allows the installation of one or two electric motors, and the development of both two- and four-wheel drive electric models. MEVP2 allows batteries that combine modularity in its height and also in its length to tailor the battery to the type of vehicle. The platform allows assembly of a product variety of eight electric models in segments B, C and D of the four brands (year 2022).

4.2.3 | Production system

The sharable production system is particularly relevant in the case of this carmaker. The carmaker’s standard integrated production system was deployed in the plants of the production network. This standard production system was the result of a process of identification and sharing of the best practices at the carmaker plants and has been replicated for the electric vehicle production plants. A circular economy production model has been implemented in a pilot plant, the aim being to spread the circular economy to the other plants in the electric vehicle production network.

4.2.4 | Production network

With this MEVP2, the plan for 2022 is that three plants (of 12 plants in the carmaker’s European network) form the electric vehicle production network. The locations of these plants are geographically concentrated in France and the UK, and the production from them is destined for the European market. Regarding coordination mechanisms, a common corporate operations management is shared among plants of the carmaker.

The plant roles are assigned based on plant focus. The assignment of roles to production plants is driven by economies of scale and by flexibility to produce different product variants. These plants are relatively autonomous in terms of production in relation to other plants in the network. They play a role as hubs for electric vehicle production in the Manufacturer’s European production network.

In terms of network outputs, operational flexibility for transferring production models is allowed among the three plants. Eight electric models with a production volume of five hundred thousand units will share the manufacturing resources of the production network (year 2022).

4.3 | Platform MEVP3

4.3.1 | Sustainable development

With the sustainable deployment strategy, the manufacturer foresees the production of 1.5 million electric vehicles in 2025 (in three different modular electric vehicle platforms). This objective implies high-volume series production of electric vehicles that requires an efficient adoption of these new platforms. This strategy started in 2019 with the production of vehicles under MEVP3 across the manufacturer’s brands.

In terms of sustainability, MEVP3 is focused on a sustainable production process. The sustainable strategy includes the objective of carbon-neutral production at all MEVP3 locations in Europe. The initial goal is to reduce the environmental impact of production processes by 2025 in areas such as energy usage, CO₂ emissions, waste and the use of water by 45% per vehicle compared to 2010.

In terms of network coordination mechanisms, the adoption of MVEP3 has gone hand in hand with the deployment of a common strategy on the production process and facilities to produce with a neutral carbon balance. The plants of the production network share knowledge and best practices on sustainable procedures and sustainable technology in the facilities.

4.3.2 | Product design

MEVP3 is made up of compatible structural modules and allows variations in structural dimensions. The architecture is built around a flat rectangular battery located between the axles and on the floor of the platform. These batteries are modular, which means they can be adapted to each vehicle. Thus, the wheelbase, the distance between the bottom bracket and the front axle, and the track width can be varied. The axles are offset far apart, ensuring short overhangs. The drive system consists of one or two electric motors integrated into the axles, including power electronics and transmission. The auxiliary units (e.g., steering box) are located in the front part of the vehicle. This platform is designed exclusively for electric vehicles. Other motorisations are not included; no hybrid models will be assembled under this platform. The MEVP3 design allows a product variety of 12 different...
| **TABLE 1** Key features regarding modular electric vehicle platforms. |
|-----------------|-----------------|-----------------|
| **Sustainable development** | **MEVP1** | **MEVP2** | **MEVP3** |
| Environmental impact and regulatory requirements | MEVPs are adopted to achieve the efficiency of mass-production electric vehicles, complying with regulatory environmental requirements. 100% of the manufacturer’s range (40 hybrid and electric models) will be electrified in 2025. | MEVPs are adopted to achieve the efficiency of mass-production electric vehicles to achieve carbon neutrality in 2050. | MEVPs are adopted to achieve the efficiency of mass-production electric vehicles, complying with regulatory environmental requirements (1.5 million electric vehicles in 2025). |
| Sustainable product design | The platform is focused on sustainable product design. The platform is designed to limit CO₂ emissions. Weight reduction using high-performance materials. This design also includes fewer components than the platform it replaces in order to facilitate disassembly and recycling. | The design is created to improve energy consumption, using lightweight. Moreover, the modular battery design seeks to reduce vehicle weight. The batteries are extra-thin, allowing vertical modularity (they can be used as stackable modules). | MEVP3 is focused on sustainable production process. The platform is implemented with the adoption of carbon-neutral production processes, energy and water usage, CO₂ emissions, and waste generated. Coordination mechanisms among plants are intensified to deploy the common carbon-neutral production processes. Knowledge transfer specifically on sustainable procedures and sustainable production technologies. |
| Sustainable production process | MEVP2 is implemented with a pilot circular economy production model (maintenance, remanufacturing and recycling). This pilot process includes a line for dismantling end-of-life vehicles. This new facility recovers different parts and materials as well as the batteries. | | |
| Product design | Skate-board design (batteries in the rear of floor and electric motors in the axles). The drive architecture includes a combustion motor in the front part of the vehicle. | Scalable design with a modular battery that can be adapted to each vehicle. | Skate-board design (batteries in the floor and electric motors in the axles). Scalable design built around a modular battery that can be adapted to each vehicle. |
| Modularity | Modularity through compatible modules to allow structural dimensions variation. MEVP1 includes models in segments B and C. | Modularity through compatible modules to allow structural dimensions variation. MEVP2 includes models in segments B, C and D. Modularity of the battery (in height and in length) to include models from different ranges. | Modularity through compatible modules to allow structural dimensions variation. MEVP3 includes models in segments B, C and D. Modularity of the battery (in width and in length) to include models from different ranges. |
| Production system | Deployment of a common modular toolkit strategy on production process. This includes fully robotised body-in-white workshops and mixed-model final assembly lines where internal combustion engine and electric vehicle models can be shared. | Deployment of a standard carmaker integrated production system. | Implementation of multi-brand mixed-model assembly lines. |
4.3.3 | Production system

The plants will be configured for the new MEVP3 and entirely converted from internal combustion engine vehicle production to exclusively electric vehicle production. The conversion of the plants also includes a plan to produce with a neutral carbon balance. Regarding production systems, multi-brand production has been stepped up. In some plants, multi-brand production has been implemented for the first time with MEVP adoption. This has been done particularly on the mixed-model final assembly lines, which must be shared by different models. Plant-1, in which production under MEVP3 was launched, produces six models of three brands, including a premium brand. This flexible production system ensures flexible changes of models without losing production capacity (in plant-1 production can reach 1500 vehicles/day).

4.3.4 | Production network

With this modular architecture, the plan for 2022 is that five plants (of 24 plants in the manufacturer’s European network) make up the electric vehicles production network. The locations of these plants are geographically concentrated in two countries (four in Germany and one in the Czech Republic) and the production from these plants is destined for the European market.

Regarding plant roles, they are assigned based on plant focus. The assignment of roles to production plants is driven by economies of scale and flexibility: economies of scale to achieve high-performance specialised products (electric vehicles) and high volumes, and flexibility to produce different product variants. These plants play a role as hubs for electric vehicle production in the Manufacturer’s European production network and they are relatively autonomous in relation to the other plants in the network.

In terms of networks outputs (expected for the year 2022), the operational flexibility for transferring production of the MEVP3 models will be possible among five plants. A total of 700,000 units of 12 electric models can share the manufacturing resources of the production network.

Table 1 summarises the key elements of each manufacturer in the implementation of their modular electric vehicle platforms.

5 | DISCUSSION OF RESULTS AND CONCLUSIONS

5.1 | Theoretical contribution

Regarding the product architecture design (research question RQ1), MEVPs are a modular product architecture that combine traditional
efficiency with sustainability requirements in their design. MEVPs are made up of compatible structural modules that allow structural dimension variations just like MPs (Buiga, 2012; Schuh et al., 2013) and that integrate the new specific elements of electric vehicles in a skateboard design (batteries in the floor and electric motors in the axles). Modularity of MEVPs derived from compatible structural modules allows a product variety that includes models from different segments (sizes) in their design. Moreover, the electric drive system architecture and modular batteries that MEVPs integrate allow this platform to assemble a product variety defined by a broad model range in terms of power and autonomy.

Regarding production systems (research question RQ2), MEVPs have been adopted by means of efficient production systems to achieve mass-production and to launch new electric vehicle models quickly. These efficient production systems have been deployed using flexible production processes to produce high volumes of different models, and versatile facilities to avoid large investments when launching new models.

The production networks resulting from MEVP adoption (research question RQ3) are geographically concentrated in a few countries in contrast to the geographical dispersion of production networks resulting from the modular product architecture pointed out by the literature (Lampón & Rivo-López, 2021). MEVPs have been implemented in some plants of the manufacturers’ European production networks that act as hubs for electric vehicle production. Regarding coordination mechanisms, although the plants in the network are relatively autonomous in terms of production, they still maintain traditional knowledge sharing with other plants (e.g., benchmarking, expertise exchange) (Lampón et al., 2019; Norouzilame & Wiktorsson, 2018).

In terms of plant roles, the automobile manufacturers have assigned roles to their plants in electric vehicle production networks based on plant focus criteria. No location factors are key in this assignment. In particular, these roles have been mainly driven by economies of scale to achieve high-performance specialised products and high volumes. This finding is an important difference when compared to the role of plants using modular architecture pointed out by previous studies, where the driving forces are location factors and economies of scope in an attempt to exploit comparative location advantages and to facilitate the transfer of the models among plants (Pashaei & Olhager, 2019).

The development of MEVPs is part of a comprehensive sustainable development strategy being deployed by the automobile manufacturers (research question Q4). MEVPs have been adopted to achieve the efficiency of mass-production electric vehicles to comply with regulatory environmental requirements. In terms of sustainable product design and sustainable production processes, although the results are not unanimous, various MEVP adoption initiatives have been implemented. MEVPs are designed to limit energy consumption and are focused on weight reduction through the use of high-performance materials or extra-thin batteries. Moreover, a reduction in component numbers is used in some of the designs to facilitate
disassembly and recycling at the end of the vehicle’s useful life. Finally, in order to adopt MEVPs, the production system has incorporated carbon-neutral production processes or circular economy production models, which include aspects of remanufacturing and reusing. To deploy these common carbon-neutral production processes, knowledge transfer specifically on sustainable procedures, and sustainable production technologies have been implemented among the production networks’ plants.

5.2 | Practical implications

Different practical implications can be derived from the research. The results show that carmakers are not following the same line when deciding to adopt MEVPs. There is no single model that clearly stands out. MEVP adoption is in its early stages and, therefore, the initiatives being implemented can be considered experimental. This is not a new situation for carmakers when faced with a new organisational choice. In fact, there are similarities with initial development of modularization process in this industry, in particular with the first modular experiments in Brazil where carmakers tried to test a new organisational model in order to seize the opportunity opened by modular production (Lung et al., 1999). Given the present context, characterised by some uncertainty in the technologies linked to clean energies and by the embryonic state of MEVP adoption and the initiatives being implemented, automobile manufacturers should maximise their efforts to develop and experiment with novel formulas in this new type of modular organisation, focused on sustainable development. Moreover, benchmarking, collaboration, and the creation of alliances between automobile manufacturers for the design and manufacture of MEVPs should be included as priority elements in their strategic plans.

On the other hand, MEVPs form part of a comprehensive strategy of automobile manufacturers for sustainability that goes beyond the industry itself. The different initiatives on sustainable design such as the weight reduction to save energy or the use of fewer components to facilitate recycling, and on the sustainable production process such as the implementation of carbon-neutral production processes have a relevant impact on society in general. In fact, these initiatives have a direct influence on meeting some of the SDGs such as SDG7 (clean energy), SDG12 (sustainable production and consumption) or SDG13 (climate). Therefore, institutions, particularly the governments of countries with a strong presence in automobile industry, should implement active industrial policies in MEVPs adoption. The introduction of investment incentives or the fostering of a favourable technological environment that is suitable for MEVPs development and production are possible recommendations for public policy that can be derived from the research.

5.3 | Future research

The analysis in this research into MEVPs has focused on the design and production stages within the product lifecycle. Although some aspects of use and end-of-life have been identified, they have not been looked at in depth. Future research could analyse the adoption of MEVPs during the use and end-of-life of the product lifecycle.

At the same time, MEVPs are not fully implemented in all three of the analysed cases. Future research could carry out longitudinal studies to analyse the evolution of implementation. In particular, comparison could be made of the proposed objectives and those that were finally achieved by implementation. Furthermore, a comparison could be made of the impact in terms of sustainability and efficiency resulting from the differences in the strategies used by each automobile manufacturer when adopting their MEVPs.

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ENDNOTES

1 The segment concept is used in the automobile industry to classify the different models. Segments are defined and classified basically based on size. According to the European Commission: mini cars (segment A), small cars (segment B), medium cars (C), large cars (D) or executive cars (E).

2 The main shops of an automobile assembly plant are the body shop, where the raw materials pass initially through a stamping process, then the welders assemble the stamped parts to create the body in white; and the final assembly shop, where different parts and modules are assembled to make a marketable product (Patchong et al., 2003).

3 Availability of data statement: Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

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**APPENDIX A: Information covered by the questionnaire**

- **Block 1 – Sustainable development**
  - A. Sustainable development goals:
    - a. Electric vehicles production
  - B. Sustainable development initiatives:
    - a. MEVP and environmental impact and regulatory requirements
    - b. MEVP adoption and sustainable product design
    - c. MEVP adoption and sustainable production processes

- **Block 2 – Product design**
  - A. Platform:
    - a. Scalable design and drive system architecture
    - b. Features of the batteries
  - B. Modularity:
    - a. Number and types of compatible structural modules included
    - b. Variation in the structural dimensions
  - C. Product variety:
    - a. Models and segments involved in the MEVP design

- **Block 3 – Production system**
  - A. Compatible and flexible production system:
    - a. Production processes standardisation
    - b. Versatile facilities implementation

- **Block 4 – Production network**
  - A. Production network configuration (geographical dispersion):
    - a. Number and location of production plants involved in MEVP adoption
  - B. Production network coordination mechanisms:
    - a. Knowledge share and transfer
  - C. Plant roles assigned:
    - a. Location factors and plant focus criteria
  - D. Production network outputs:
    - a. Operational flexibility, economies of scope and economies of scale