Mirroring in production? Early evidence from the scale-up of Battery Electric Vehicles (BEVs)

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Abstract

The mirroring hypothesis is central to modularity theory, positing isomorphism between technical interdependencies of a product and organizational arrangements. When a product's design becomes more modular, a full mirroring response would change both its manufacturing and its supply chain.

We evaluate this prediction for electric vehicles (EV), observing whether automakers have mirrored the modular EV architecture in either internal production processes, external sourcing arrangements, or both.

Our data from 17 automakers show that, to date, EVs are manufactured in their assembly plants alongside conventional internal combustion engine vehicles (ICEV). Fully EV plants utilize essentially the same production process. Furthermore, automakers make - or ally to make - key EV components, rather than outsourcing them.

We discuss the implications of this partial mirroring for modularity theory and ask whether these arrangements will persist once EV sales surpass ICEVs.

Keywords: modularity, mirroring, design, production, technological change, electric vehicles

Introduction

The theme of this ICC special issue is "The Power of Modularity" and the Call for Papers highlights the tremendously fruitful scholarship spurred by the application of modularity theory, formulated in Baldwin and Clark's *Design Rules* (2000), to a wide range of phenomena. As their title signals, "design" is central to Baldwin and Clark, across levels of analysis -- from the physical specificity of studying products as technical artifacts to the longitudinal and dynamic analysis of the design of the organizations (both structure and process) that bring those products to market. At an industry level, the careful attention to product and organizational design and their interrelationship yields insights into the boundary of the firm, competitive dynamics, innovation processes, and industry evolution.

Baldwin and Clark (1997, 2000) describe three dimensions of a product's modularity: modularity-in-design (MID), modularity-in-use, (MIU) and modularity-in-production (MIP). While MID unsurprisingly draws the lion's share of both theoretical and empirical attention, and MIU is a particular focus for digital products and services, MIP is, in our view, understudied.

We take the position in this paper that watching what happens in production is highly valuable in clarifying one of modularity theory's central tenets: the "mirroring" hypothesis (Colfer and Baldwin, 2016; Henderson and Clark, 1990). This hypothesis, as stated in the Call for Papers, asserts that "organizational ties within a project, firm, or group of firms (e.g., communication, collocation, employment) will correspond to the technical dependencies in the work being performed."

While there is ample empirical evidence for the mirroring hypothesis, it is not universally supported. Under certain boundary conditions, "partial mirroring" occurs – and may be beneficial. Colfer and Baldwin (2016) argue that at a time of technological change, the firms integrating complex systems will face incomplete knowledge about underlying technical interdependencies and will prefer integrated organizational arrangements until their understanding improves. This can either indicate a transitional period in which organizational changes lag product design changes – or be the outcome of a deliberate strategic choice.

We argue – and present evidence here – that careful attention to modularity-in-production adds richness to what we know about "partial mirroring" – why it occurs, how durable it will be, whether it can be stable despite the implied tension and misalignment, or whether that very

misalignment will eventually drive dynamics that lead to full mirroring. We do so in the context of a dramatic recent change in the product architecture of the automobile whose "dominant design" was established in the mid-1920s and has remained quite stable for nearly a century.

The carbon neutrality objectives in 2050, resulting from the Paris agreement in 2015, as well as the numerous global regulations concerning the reduction of CO2 and other polluting emissions are putting the automotive industry under great pressure to switch rapidly from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs).

Electrification changes the dominant design of the automobile – on that there is no disagreement. Electric powertrains and HV battery systems have a modular, rather than integral, product architecture, in that the technical interdependencies across components are minimal and coordination requirements can be minimized in how interfaces are designed. This "modularity-in-design" for the powertrain offers new ways to boost performance (e.g., via multiple e-motors per vehicle), brings new suppliers into the auto industry, and creates new competitive dynamics. From the perspective of "modularity-in-use", it certainly affects the user experience of customers, who must recharge batteries in a manner (and duration) very different from gas station refueling. Shouldn't this massive change affect production as well?

While "modularity-in-production" is not as well developed in ***Design Rules*** as "modularity-in-design" and "modularity-in-use", we find clues in how Baldwin and Clark treat production to guide our theorizing. We also examine the copious modularity literature to find the subset that explores "modularity-in-production" and the relationship between MID and MIP – and draw upon that subset to propose two subcategories of MIP from which our hypotheses are drawn. Finally, we interpret our empirical data on EVs to address the fundamental evolutionary question of whether the current "partial mirroring" will be transitional or whether it could be stable as part and parcel of how incumbent automakers compete in the EV space.

Our research question, therefore, is "will a change in dominant design that affects modularity-in-design be mirrored in a corresponding change in modularity-in-production?" Adding the empirical context, we are exploring whether the integration of the High Voltage (HV) electric battery and electric powertrain systems into the existing dominant design of a vehicle will trigger a move towards full mirroring in production -- or not. If not, why does this occur and what future dynamics do we predict?

This paper is organized in five sections. Section 1 presents the theoretical context, emphasizing the original Baldwin and Clark (1997, 2000) formulation of the MID-MIP relationship and proposing hypotheses from two subsets of the literature, which we identify as MIPP (modularity-in-production-process) and MIPS (modularity-in-production-system). In Section 2, we introduce the automotive industry context and Section 3 is devoted to research design and methodology. Section 4 presents the results of our empirical study on the current strategic choices of automakers, incumbents and newcomers, with respect to EV production and the supply of the two main systems, namely HV batteries and electric powertrains. In Section 5, we discuss our results and draw out their implications vis-à-vis modularity in production and the mirroring hypothesis. In Section 6, we present our conclusions as pertains both to future research and the future strategies of EV actors in the fast-changing mobility sector.

1. Literature Review

A way to parse the voluminous modularity literature is by distinguishing two subsets. The first is focused on modularity applied to the product as an artifact and the processes of how it is designed, manufactured, and used. The second examines implications of modularity for the boundaries of the firm (make vs. buy), organizational design, industry architecture, and competitive dynamics. While both are shaped by seminal work in complex systems theory (e.g., Simon, 1962), each was applied to different technical domains and economic phenomena.

The former literature is situated primarily within engineering, operations, computer science, and project management domains. Influential early works in computer science (Mead and Conway, 1980; Parnas, 1972) have been generalized in engineering design texts (Nevins and Whitney, 1989; Steward, 1981). The Design-Structure-Matrix (DSM) – developed by Steward with Eppinger (1991)– was an influential visual tool for depicting the relationship between a product's functions as they are mapped on its structure – aka product architecture.

Subsequent theorizing by Ulrich (1995) established a product architecture continuum from modularity (1-to-1 mapping of function to component) to integrality (1-to-many or many-to-1 mapping of function to component). Engineering design researchers emphasized modularity's role in product life-cycles (Gershenson et al., 2003; Ishii, 1998) and operations management scholars linked modularity to topics such as commonality, standardardization, combinability, and flexibility (Fine, 1998; Fisher et al., 1999; Gerwin, 1993; Salvador, 2007).

The latter literature is situated primarily within strategy, management of technology, and organization theory. Some literature stayed closely tied to the study of product architecture, notably Henderson and Clark (1990) where "modular" was one type of innovation. But, according to Campagnolo and Camuffo (2010), modularity in these management-related fields primarily moved to the organizational and industry level of analysis, where researchers explored (i) the link between modularity and outsourcing and the impact on knowledge boundaries (Brusoni et al., 2001), (ii) the consequences of modularity for value chains -- how are they organized? how global?– (Gereffi et al., 2005; Sturgeon, 2002); and (iii) industry architecture and competitive advantage -- who does what? who gets what? – (Fixson and Park, 2008; Jacobides, 2006; Jacobides et al., 2006; Jacobides and Winter, 2005).

A significant proportion of this research was focused on the automotive industry, which, after establishment of a dominant design, had a highly integral product architecture and a high degree of vertical integration. The issue of the evolution of modularity in the automotive industry has attracted increased interest from practitioners and researchers (Fourcade and Midler, 2004; Jacobides et al., 2016; MacDuffie, 2013, 2006; Ro et al., 2007; Sako and Murray, 1999; Takeishi, 2001). Althought grounded in analysis of product architecture, this work largely examined strategy issues at the organizational and industry level of analysis.

These two sets of literature inform our hypotheses differently. We will use the term "modularity-in-production-process" (MIPP) to characterize the predominantly product-focused literature from engineering and the production processes associated with MID. We will use the term "modularity-in-production-system" (MIPS) to characterize the literature from strategy, management of technology, and organization design that is predominantly focused on the boundaries of the firm, industry architecture, and competitive dynamics, and which analyzes "who does what" and "who gets what". Going forward, when we want to explore the relationship between MID and MIP, we will develop two lines of analysis to pick up how design relates **both** to production process and production system, i.e. examining both MID-MIPP and MID-MIPS.

Now we return to Baldwin and Clark's work (1997, 2000), which stands out also for spanning these two subsets of literature. Distinctions between design and production are fundamental to Chapter 2 of *Design Rules*, "Microstructures of Design"; the definitional premise is that design is a separable stage from production (further separable from use), with the design process generating the design instructions that are carried into production. Chapter 3, "What is Modularity?" offers a

short sidebar (Box 3.2, p. 78) that distinguishes modularity-in-design (MID); modularity-in-production (MIP); and modularity-in-use (MIU).

Yet on the whole, Baldwin and Clark stay closely focused on modularity of product design (MID), relying on DSM visualization of the relationship between technical features and design tasks to advance the hypothesis of "the fundamental isomorphism between design structure and task structure" (2000, p. 46), later reframed as the "mirroring hypothesis". As far as production goes, in Baldwin and Clark's view, it was already largely modular; they write "Manufacturers have been using [modularity] for a century or more because it has always been easier to make complicated products by dividing the manufacturing process into modules… (1997, p. 86). Put differently, they expect high MIPP in modern mass production manufacturing whether MID is high or low.

Baldwin and Clark also reach readily to the implications of modular design for industry structure and competitive dynamics. Their central example in *Design Rules* is, of course, the IBM 360 mainframe computer, an explicitly modular design. They also provide an extended example of a modularity initiative for the outsourcing of cockpits (instrument panels) from automaker Mercedes-Benz to mega-supplier Delphi, saying "under intense pressure to reduce costs, accelerate the pace of innovation, and improve quality, automotive designers and engineers are now looking for ways to parcel out the design of their complex electro-mechanical subsystems (1997, p. 87). Moving towards modular design, in their view, would also move the auto industry towards a more modular industry architecture. Put differently, they anticipate higher MIPS as MID rises.

As noted, Baldwin and Clark pay attention to production and use as well as design. However, after creating these distinctions, Baldwin and Clark demonstrate repeatedly that design is at the heart of their project, with almost no further mention of production in the book. Others would take up digging deeply into MIP and its relationship with MID.

We found a small number of studies that look explicitly at the relationship between MID and MIPP. Most draw on the automotive industry for empirical evidence. Jacobs et al. (2011) use detailed survey responses from 57 Tier 1 suppliers in the US auto industry to model different relationships among MID, MIP, manufacturing agility, and performance. Their measures include product modularity, i.e. MID variables such as interchangeable parts for flexible configuration of a high variety of products and process modularity with some MIPP variables such as flexible manufacturing equipment and use of cellular manufacturing. In the best-fitting model, product

modularity is strongly linked to process modularity and the combination of product and process modularity leads directly to manufacturing agility and high performance. As for the exact mechanism, they write "A way modularity can boost manufacturing agility is through product decomposability. Modules built in parallel, without adverse assembly consequences, can decrease manufacturing lead time" (p. 133).

Kubota et al. (2017) provide a literature review, also based on the auto industry, that examines the MID-MIP relationship for both MIPP and MIPS aspects. They find that some studies assume directionality of causality from MID-based product variety strategies to both MIPP (functional commonality coupled with customized add-ons) and MIPS (outsourcing decisions mediated by level of interdependence across modules) activities. Other studies assume the reverse causality, seeing MIPP decisions about standardization and MIPS decisions about outsourcing and co-design with suppliers as the key variables leading to increased MID. Overall, Kubota et al. (2017) conclude there is no empirical evidence to support only one direction of causality, echoing general modularity systems theory (Schilling, 2000), which states that change in one system can affect any other system, in a dynamic movement towards "fit".

Sako and Murray (1999) were one of the first to pick up Baldwin and Clark's use of MID, MIP, and MIU and to apply them to an explicit cross-industry comparison of the computer and automotive industries. They concur with the observation that, from a MIPP point of view, the automotive industry is already quite high in modularity; the question is whether MID will increase and what the consequences will be for MIPS. They then speculate about three trajectories by which MID could arise: (i) The focal firm could first modularize the design internally (within vertical integration) and then outsource it to suppliers (MID leading to MIPP and then MIPS); (ii) The focal firm could outsource immediately and encourage the supplier to make the design more modular (MIPS leading to MIPP and then MID); and (iii) Outsourcing and co-design with the supplier could boost MIPS, MIPP, and MID simultaneously.

Returning now to our research question "will a change in dominant design that affects modularity-in-design be mirrored in a corresponding change in modularity-in-production?", what do we anticipate in a situation in which the dominant design shifts towards high MID? Will MIPP and/or MIPS rise as well? Put differently, will the MID-MIPP and MID-MIPS relationships be fully or partially mirrored when MID increases?

If MIPP is typically high for modern production processes at high scale, a boost to MID opens a much wider scope for strategic choices vis-à-vis MIPS. As Sako and Murray point out, design can stay internal to the firm until learning occurs, then production can be outsourced. Or outsourcing can happen first, with pressure on the supplier to undertake MID. Each of these scenarios identify partial mirroring as a stage in transition (potentially) to full mirroring. Yet much past research (Furlan et al., 2014) finds that modular design is often found together with integrated organizational arrangements during a period when components are technologically dynamic. Under these circumstances, firms could be choosing partial mirroring as deliberate long-term strategy rather pushing through it as a transitional stage. This suggests that MIPP and MIPS might not follow an upward move in MID.

In this specific empirical context, EVs are bringing a big boost in MID as HV batteries and electric powertrain are more modular in comparison to ICEVs. Our research inquiry is to understand what happens to MIP – or more specifically to both MIPP and MIPS. We pursue this inquiry by tracking the results of three choices about EV production made by automakers.

First, are the EVs manufactured within the regular assembly plants of automakers, mixed in with ICEV models, or are they manufactured in a separate facility using a dedicated process?

Second, for the HV batteries that EVs require -- a new module that moves the dominant design towards high MID, will automakers buy; ally to make; or make batteries themselves?

Third, for the electric powertrain in EVs, inherently higher in MID than ICEV powertrains, will automakers buy; ally; or make e-powertrains themselves?

2. Industry Context

The automotive industry, according to both historians and scholars of industry evolution, has been anchored in a dominant design since the 1920s (Borgstedt et al., 2017; Henderson and Clark, 1990; Suárez and Utterback, 1995). The consolidation of a dominant design contributes greatly to the architecture of an emerging industry (Baldwin and Clark, 2000). This is certainly true of the automotive sector where settling upon an internal combustion engine, fueled by gasoline, with a drivetrain, plus a enclosed metal body, suspension, steering and brakes, tires (and so forth) thereafter shaped product design decisions, regulations, industry standards, component technologies, and, generally speaking, interfaces (Jacobides et al., 2006; Jacobides and MacDuffie,

2013; Jacobides and Winter, 2005), as well as knowledge and technical capabilities of firms (Zirpoli and Camuffo, 2009).

Indeed, since the beginning of mass production in the early 20th century, automakers have continuously developed their capabilities at designing and coordinating the production of integral architecture vehicles through a hierarchical value chain (Fujimoto, 2017; MacDuffie, 2013). They rely on their design agility resulting from (i) a high base of internal R&D knowledge consistent with a "know more than you make" (Brusoni et al., 2001) strategy, (ii) the continuous integration of evolving component technologies (Wells and Nieuwenhuis, 2012) and (iii) the persistence of their operational routines (Zirpoli and Camuffo, 2009).

In recent years, automakers are under growing and persistant pressure to switch from ICEVs to EVs due to a global set of increasingly stringent environmental regulations, including:

1. Reduction of emissions to a maximum threshold (e.g., 95 g of CO2 /km in Europe by 2021) or imposing a minimum threshold of EV sales, (e.g., 22% in California by 2025);
2. Reduction of the level of pollutants to a maximum threshold, e.g., Euro6d in Europe;
3. Internal combustion vehicles banned or phased out (Burch and Gilchrist, 2018);
4. The goal of carbon neutrality by 2050, from the Paris Agreement, requiring a ban on the sale of new internal combustion cars by the second half of the 2030s.

Electrification consists of modifying the energy source, replacing the fuel tank with a HV battery, the powertrain, by using an electric motor instead of an internal combustion engine and changing the way power is transmitted and modulated to the wheels. In itself, the mere modification of the energy source and the powertrain is sufficient to transform the industry dominant design in its oldest fundamentals —particularly when we consider the knock-on effects on the design of the entire vehicle and their consequences along the value chain (Fuchs et al., 2013; Fujimoto, 2017; Klug, 2013; Muniz and Belzowski, 2017, Von Pechmann et al. 2015).

While different technological strategies[1] for EVs have been observed over the past two decades, strategic decisions to commit to majority electrification, via BEVs, is quite a recent phenomenon. Growth in the EV market faced initial starts and stops based on vehicle availability and only over the past 5 years has the market percentage climbed steadily, albeit slowly, reaching about 4% of all vehicles sold in 2020. This global market share conceals substantial differences in market penetration across countries. China has been the leader for the past several years, though in 2020, total EV sales in the EU surpassed China's level[2]. While EV "tipping point" projections

have been made for years, the recent commitments by automakers, ranging from GM to Volvo to Volkswagen, to make a full transition from ICEVs to EVs by 2035[3] (or sooner) demonstrates the cumulative effect of environmental regulations described above.

As further context, considering that the automotive industry is a representative archetype of the "*Hierarchy-based Value System*" (Jacobides et al., 2018), we next present, in broad terms, the most common organizational architecture of automakers, particularly with respect to production. The automotive industry's hierarchical value chain is strongly managed by a focal firm, namely an automaker or Original Equipment Manufacturer (OEM) acting as the system integrator whose role is to create the product design through a complex division of labor among its own staff (R&D, product and process engineering, product design teams) and outside suppliers; these suppliers are organized in tiers, with top tier (larger and more technically sophisticated) suppliers, aka Tier 1, overseeing the efforts of the Tier 2 suppliers at the next level of the hierarchy, and so forth.

We present a visual depiction of the automotive industry's architecture – specifically "who does what" in the division of labor -- in Figure 1. Automakers make in-house powertrain and chassis components or systems as well as the painted body and the final assembly of the vehicle. Tier 1 suppliers deliver systems (e.g., braking) and big modules (e.g., assembled seats), Tier 2 suppliers usually deliver main parts or components while Tier 3 or 4 suppliers provide subassemblies and raw material. Distribution and sales are also the responsibility of automakers; this channel oversees the retail and repair network and a manufacturer's network coexists with independently-owned dealerships.

--- Figure 1 to be included here – see file Figure 1.jpg ---

Figure 1: A simplified presentation of the automotive industry architecture (make perimeter)

As we want to focus on how a significant change in product architecture can lead to change in the manufacturing process (i.e. the make perimeter), we introduce the most common vehicle production system in Figure 2 below. Body parts (mainly still metal) are stamped in upstream processes and then assembled, via joining technologies (welding and glueing), in a monocoque body. The body is then protected against corrosion and painted in the color requested by the final customer. Vehicle assembly consists of installing all the components, parts and modules, delivered by the inbound logistics, in the painted body to end up with a vehicle ready to start at the end of the line and to be placed in the outbounds logistics circuit after the static and dynamic adjustments and controls have been carried out.

Inbound logistics includes the delivery, by suppliers, of the materials, products, components, parts and modules required to manufacture the vehicle at each process stage plus the engines, gearboxes, transmissions, axles and chassis components produced in internal powertrain plant(s).

--- Figure 2 to be included here – see file Figure 2.jpg ---

Figure 2: Vehicle production system description

We expect that EVs can potentially affect *every* stage of the make perimeter of the automotive industry, from raw materials (for batteries) to repair and service, shown in Figure 3.

--- Figure 3 to be included here – see file Figure 3.jpg ---

Figure 3: Expected impacts of electrification on on the automotive industry architecture (make perimeter)

One leading hypothesis on electrification is that because of the greater modularity of the electric powertrain plus the centrality and higher price of the HV battery system compared to conventional ICEV systems, specialized suppliers would gain power in relation to automakers and overturn traditional hierarchical relationships, taking the dominant value-adding position in the industry. A related question is whether automakers, under the pressure of the disruption of the dominant design driven by electrification, will still have the capability of producing EVs in their existing manufacturing assets according to the process sequence described above.

Consequently, because the BEV involves a fundamental transformation of the dominant car design and is currently developing at an accelerated rate, the automotive industry provides us with an ideal context to address our research question: "Will a change in dominant design that affects modularity-in-design be mirrored in a corresponding change in modularity-in-production?" or reframed in terms of modularity theory, *"Will a change in dominant design that boosts MID also lead to increased MIPP or MIPS?"*

Hence, given the industry architecture described above, we assess the current strategic choices of automakers, both incumbent and newcomers with respect to manufacturing (make), purchasing (buy), or joining forces (ally) to produce EVs, for both the assembly plant and the sourcing of the two main systems, namely the HV battery and electric powertrain. Consequently, we have multiple units of analysis: the production system of EVs and the value chain of key EV components, including battery pack and electric powertrain components. Next we explain the research methodology for gathering the data needed to address our research question.

3. Methodology

3.1. Case selection

We utilize a design with multiple units of analysis embedded within each case (Yin, 2009).

--- Figure 4 to be included here – see file Figure 4.jpg ---

Figure 4: Multiple case study description

We examine nearly the population of EV automakers, including all incumbents[4], comprising roughly 70% of global sales, plus five new all-EV automakers (see Table 1):

	Company name	Region of origin	Status
1	BMW	Europe (Germany)	Incumbent
2	BYD	China	Newcomer
3	Daimler	Europe (Germany)	Incumbent
4	FCA	USA / Europe (Italy)	Incumbent
5	Ford	USA	Incumbent
6	GM	USA	Incumbent
7	Honda	Asia (Japan)	Incumbent
8	Hozon	China	Newcomer
9	Hyundai	Asia (South Korea)	Incumbent
10	Lucid Motors	USA	Newcomer
11	Nissan	Asia (Japan)	Incumbent
12	NIO	China	Newcomer
13	Groupe PSA	Europe (France)	Incumbent
14	Renault Group	Europe (France)	Incumbent
15	Tesla	USA	Newcomer
16	Toyota	Asia (Japan)	Incumbent
17	VW	Europe (Germany)	Incumbent

Table 1: List of selected automakers for case study

3.2. Analytical framework

With regard to EV production, we want to know whether automakers produce EVs according to an *adapted standard process* or to a *new EV-specific process.* If we observe that EVs are (i) produced according to the standard manufacturing process (as described in figure 2 above), and

(ii) that required process modifications, in all stages, are achieved by reusing the dominant design rules of the ICEV, then we affirm that it is produced according to an *adapted standard process*; if at least one of the two conditions above is not met, then it is a *new EV-specific process*. Table 2 shows the template we use to assess the EV production system.

Automaker	Vehicle	Assembly plant	Use of standard assembly process?	Does process reuse ICEV design rules?	Type of process
Name of the automaker	Nameplate of the vehicle	Name, location of Existing or Greenfield plant	Yes / No	Yes / No	*adapted standard* or *new EV-specific process*

Table 2: Template for vehicle production system observation

To assess the two component value chains, we need to define each system, functionally, and then determine the relevant perimeter. The battery system consists of modules, electrically interconnected by wiring and connection devices, plus a cooling system, all combined in a physical "pack" with a lower tray, an upper cover and structural reinforcements. The modules are composed of multiple cells, each with basic battery components, e.g., electrodes, electrolyte, integrated in a specific housing. Besides the hardware, Battery Management System (BMS) software performs vital functions, overseeing the charging process and the energy supply while constantly monitoring the battery's thermal and electrical status. Across these four EV battery system components -- the BMS, the battery pack, the modules, the cells -- we sought data to categorize the value chain of each EV producer as shown in Table 3.

DESIGN PERIMETER	MAKE, BUY, ALLY Global Players Strategies – Incumbent companies and newcomers								
BMS	MAKE	BUY	MAKE	MAKE	MAKE	ALLY	MAKE	MAKE	MAKE
Battery pack			BUY				ALLY		
Modules				BUY				ALLY	
Cells					BUY				ALLY

Table 3: Template for battery system value chain observation

We identify nine possible value chain strategies for an automaker vis-à-vis the battery system, identified by column from left to right: 1) Vertical integration of all four; 2) Buy all four; 3) Make the BMS[5] and Buy battery pack,modules,cells; 4) Make both BMS and battery pack, Buymodules cells; 5) Make both BMS, battery pack, modules and Buy cells; 6) Ally with a supplier partner (one or more) for all four; 7) Make the BMS and Ally with a supplier partner for battery pack , modules and cells; 8) Make the BMS and battery pack and Ally with a supplier partner for modules and cells; and 9) Make the BMS, battery pack and modules, Ally with a supplier partner for cells.

For the EV powertrain, we consider here it is constituted of an electric motor and a transmission plus power management/control via an inverter and converter and related software. When all these components are integrated together in a module, we call it, in this paper, "electric powertrain" (both automakers and suppliers have different names for this set).

As summarized in Table 4, we apply the same logic as for the battery system, focusing on the overall electric powertrain and the constituent components (electric motor and transmission) to identify seven value chain strategies.

DESIGN PERIMETER	MAKE, BUY, ALLY Global Players Strategies – Incumbent companies and newcomers						
Electric powertrain	MAKE	BUY	MAKE	MAKE	ALLY	MAKE	MAKE
Electric motor			BUY			ALLY	
Transmission				BUY			ALLY

Table 4: Template for electric powertrain value chain observation

3.3. Data collection

We collected data in three ways. First, we provide a descriptive case study based on observation of the integration of EVs into an existing automaker's assembly plant – one that otherwise makes all ICEVs -- to document how this is achieved. Second, to comprehend the strategic thinking of automakers, we examined public statements of their senior management teams about EV production – and then probed further via semi-structured interviews with top executives of a few automakers. Third, we gathered public information from automaker and supplier websites on manufacturing locations and procurement arrangements.

3.3.1. Case study on the integration of EVs into an ICEV assembly plant

The case study involves the integration of a BEV in the assembly process of an ICEV. The first author gathered the data by direct observation during his work in manufacturing process planning at the corporate level. It focuses on the installation of the high-voltage battery and the electric powertrain systems in the vehicle, the crucial manufacturing stages for our analysis.

3.3.2. Company accounts of EV production strategy and interviews with senior executives

From company websites, we looked for senior management team announcements of EV technological choices, sourcing agreements, or production site decisions. We supplemented this public information by doing interviews with top executives at a few automakers.

The framework of the interviews was based on the context of the empirical setting and the analytic logic outlined above. We asked three questions for the overall EV, the battery system, the

electric powertrain: 1) What is your current strategic choice about manufacturing and sourcing? 2) What were the main reasons for your decision? 3) Would you make the same decision five years later? Two of the authors carried out these interviews.

Two European automakers were chosen from among those included in Table 1. One we regard as a "first mover" with respect to EVs (Automaker1) and one we regard as a "fast follower" (Automaker2). The interviewees were top executives of the company who were centrally involved in decisions about EV strategy for manufacturing and procurement.

3.3.3. Search of industry-related websites

We searched a wide range of industry-related websites to extract, manually, relevant information about the manufacturing and sourcing of BEVs and their key components. The search and selection procedure are detailed in Appendix 1 while the "Sources of data" table is in Appendix 2. The obtained data are summarized in three tables in the results section of the paper - one per unit of analysis, across all automakers we examined. The detailed results are provided in Appendix 3 for vehicle production systems, Appendix 4 for battery systems and Appendix 5 for electric powertrain value chains.

4. Results

We open with the detailed case study of how BEVs were integrated with ICEV production at the existing assembly plant of the automaker observed by the first author. Then we present successively the results for overall EV production, the battery system value chain, and the electric powertrain value chain. Each results section includes a synthesis of the main lessons from the interviews, the public statements made by the automakers or main suppliers, and our overall assessment, shown in a summary table whose format is described above.

4.1. Study case of BEV / ICEV mixed production process

We first describe the process, see Figure 5 below, that leads to the key operation on the main assembly line that is called - universally in the automotive industry - the Mariage: the assembly of the assembled and painted body with the powertrain module, the exhaust line module, the rear axle module, the gearbox lever, the fuel tank as well as the fuel and brake pipes all pre-mounted on a pallet.[6] The installation of these different modules and components on the pallet is done in a dedicated sub-assembly line, called here "underfloor sub-assembly". The powertrain module sub-

assembly, consists of the engine cradle, parts and components of the braking, steering and suspension functions as well as the result of the engine dress sub-assembly, namely the engine, transmission, 12V harness and electronic control unit(s).

--- Figure 5 to be included here – see file Figure 5.jpg ---

Figure 5: Overview of vehicle assembly process, zoom on underfloor sub assembly and vehicle installation

We emphasize that this process has the capability to deal with many different configurations such as: diesel or gasoline engine, manual or automatic transmission, two- or four-wheel drive, and different rear axles. In other words, we confirm Sako and Murray's observation (1999) that, from a MIPP point of view, the automotive industry is already quite high in modularity.

In this example (see Figure 6), the automaker has definitely chosen a make strategy as the electric powertrain system consisting in e-motor, gearbox (both assembled in-house) and control system (inverter, converter and control unit, each component provided by a supplier and assembled in-house) is delivered by the powertrain plant. The "engine dress sub assembly line" provides the "engine compartment sub assembly line" with either a dedicated BEV cradle equipped with the electric powertrain or a dedicated ICEV cradle equipped with engine, gearbox, 12V harness and control system. We also note that chassis components are higly integrated as engine cradle and rear axle module are made in-house.

As far as the HV battery system, it is assembled in a sub assembly line (named here "battery sub assembly") and delivered, by means of a conveyor, to the marriage section of the vehicle main assembly line. The assembly process of an HV battery system uses the classic assembly operations well known to automakers: installation of parts or modules in a dedicated packaging, screwing, electrical connections as well as gluing to contribute to the closure of the pack itself. The most complex operation is the functional test at the end of the assembly which requires specific equipment and special safety conditions because it is a 400V battery.

As we have described how the two main electric systems are delivered to the appropriate assembly sections, we can now focus on what the main differences in the assembly sequences between the BEV and the ICEV are. We superimposed the BEV and ICEV operating sequences and distinguished the following cases:

1. The same operation is performed, sometimes with the dedicated BEV or ICEV component, part or module, as for instance, rear axle installation on the pallet or with specific operations such as underfloor modules and components assembly (both stations are in white),

2. There is a specific operation either for the BEV (light grey dots background) or for the ICEV (light grey grid). With no surprise, the specific operations for ICEV are related to fuel tank, exhaust line and thermal shield (installed between the body and the exhaust line) and the BEV related operations concern the 400V harness installation on the pallet and the battery assembly on the vehicle.

--- Figure 6 to be included here – see file Figure 6.jpg ---

Figure 6: Evidences of BEV / ICEV process commonalities

This in-depth overview of an in-house manufacturing strategy (BEV produced on a mixed assembly line with ICEV, manufacture of the electric powertrain and final assembly of the battery pack), explains how it is possible to integrate a BEV into a production line by exploiting the ICEV process manufacturing core technologies: (i) by keeping the marriage process, (ii) by integrating the dedicated BEV operations in the assembly sequence and (iii) by adapting or developing appropriate conveyors and assembly tools. The main disadvantage of this solution is the presence of some empty stations, which leads to line balancing issues; however, this is less of a problem compared to the advantages of reusing existing processes.

4.2. Observation of Vehicle production system

4.2.1. Summary of automakers' public statements and executive interviews

Jörg Burzer, Member of the Board of Management of Mercedes-Benz AG, Production and Supply Chain, emphasized the importance and interest of mixing ICEVs and EVs in the same assembly line "The Mercedes-EQ electric models are gradually being integrated into our existing vehicle plants worldwide. They come off the same lines as vehicles with combustion engines or plug-in hybrid drives. …. This concept is particularly advantageous because demand for electric and electrified vehicles is developing very differently by region and we can adjust our production planning accordingly on short notice"[7].

On his side, Gerald Johnson, EVP manufacturing GM, pointed out "The integration [of GM's own electric powertrain into its own car models, in effect producing everything in house] is the piece that I think is going to enable us to run further and faster. Integrating this technology into a vehicle platform in such a way that allows all the functionality that we currently offer, but the added capability of an EV—that's where I think GM is going to show out based on our track record" (Colias, 2021).

When asked about the current strategic choice in manufacturing and sourcing for the overall EV, top executive of Automaker1 declared that "*Producing the BEV and ICEV mixed on the same assembly line was an obvious decision because both vehicles shared certain design rules for the engine compartment, the manufacturing facilities had the flexibility to produce both, and it was a good solution to ensure volume flexibility in an uncertain situation*". The top executive of Automaker2 said: "*The decision was made to produce in an existing factory, whose process was adapted, both to take advantage of existing assets and process, to give flexibility to the volume and to learn how to control the mass manufacturing of electric vehicles".*

4.2.2. Global summary of observations

Automakers have taken advantage of their core knowledge to introduce EV-adapted facilities in their existing manufacturing assets. Let's take the example of the Mercedes EQC, one of the available models in the market equipped with one e-motor per axle while there is one single internal combustion engine in a car. And yet, this vehicle is produced in an existing plant, i.e. Bremen (Germany), and the well-known marriage principle (described above), highly representative of MIP, is reused in two steps for the assembly of the EQC: (1) assembly of the two electric powertrains and (2) assembly of the battery pack[8].

Based upon our detailed observation (see Appendix 3), we summarize that, apart the BMW i3 (constituted of two assembled modules - drive and life - with Carbon Fiber Reinforced Polymer external trims) and the Renault Twizy (a quadricycle with a tubular body), automakers have largely adopted an *adapted standard process* strategy.

	Number of plants	Number of Adapted standard process	Number of EV specific process
Existing plants	58	56	2
Greenfield plants	6	6	0
Grand total	64	62	2

Table 5: Summary of vehicle production system observation

These results confirm the trend that we had captured through interviews or public statements. This is further reinforced when asked if they would make the same decision today, a top executive of automaker2 said "*We confirm this decision for the next five years*" and a top executive of automaker1 declared: "*As long as there will be strong competition between automakers in terms of cost, quality and lead time with continued uncertainty about production volumes of BEVs, the answer is yes".* The latter adds: "*But once BEVs prevail over EVs, we will have to optimize our*

manufacturing plants accordingly." This suggests further rationalization of BEV assembly lines but not the establishment of totally new manufacturing processes.

4.3. Observation of the battery system value chains

4.3.1. Summary of automakers' public statements and executive interviews

Public statements on batteries from automakers provide important viewpoints, to which we add complementary statements from our interviews with automaker executives. The first statement, from Daimler-Benz, asserts the necessity for an automaker to master batteries as the essential component that determines a BEV's performance:" *The battery is a key component of electric mobility and an integral part of the vehicle architecture. The intelligence of the battery lies in a total package of hardware and software. Development, production and integration of complex battery systems are among the core competencies of Mercedes-Benz Cars*"[9].

As the battery is a key component of electric mobility, Oliver Zipse, Chairman of the Board of Management of BMW AG, highlights the importance of having a detailed knowledge of battery cell: "*The Battery Cell Competence Centre put us in a unique position: Based on current BMW i3 technology, we will be able to double the energy density of our battery cells by 2030 and double range for our customers*".[10]

While also emphasizing on the importance of mastering HV battery technology, Thomas Schmall, Member of the Board of Management of Volkswagen Group for Technology, and CEO of Volkswagen Group Components, highlights the necessity of securing supplies[11].

When asked about the production strategy for the battery system, a top executive of Automaker1 said "*What is strategic in a battery are the electrochemistry of the cells and the Battery Management System (BMS). The BMS is so strategic that we design it in-house and have it manufactured by a specialist. But it needs a refined understanding of the way the battery works and age under very different conditions and at molecular level, knowledge that battery makers sometimes know better than automakers. We had it at that time thanks to a research initiated soon enough, not sure for the future. However, the final assembly of the battery pack is not strategic because it is a classic assembly operation that can be located in the best place to minimize logistics costs. The in-house manufacturing of the battery pack was also a good opportunity to retain jobs*."

Separately, a top executive of Automaker2 said: "*For reasons of interchangeability of chemistries, the basic idea was to have modules with standardized dimensions and interfaces and*

to buy cells, meeting these specifications, from suppliers. For the design of the pack itself, it is a real work of automotive integrator and we considered that we were the best able to realize it".

4.3.2. Global summary of observations

Based upon our detailed study (see Appendix 4), we firstly observe that none of the automakers, in our sample, with the exception of BYD, which comes from the battery industry, manufacture cells: they all buy or ally. Many of the automakers have either in-house battery cell competence centers, as BMW, or have engaged cooperation with cutting-edge technology companies as announced by the Alliance Renault – Nissan - Mitsubishi[12]. It is clearly the proof that, as far as battery systems are concerned, they (aim to) know more than they make (Brusoni et al., 2001).

We summarize our results for the battery pack perimeter from the table below:

- 70% of automakers have a Make battery capability (12/17),
- 30% of automakers choose to Ally (5/17).

We also identified seven automakers that have BMS manufacturing (or design) capability. In addition, although they have entered into alliances, we can reasonably consider that, the long experience gained by Toyota and Honda in the development of PHEVs, gives them a high level of competence in the (co)design of BMS. While the collection of this information remains largely incomplete as public statements from automakers do not necessarily go into this level of detail, we nevertheless consider this to be another significant proof of the integration of the HT battery system into the automakers' core design knowledge.

As far as Ally decisions, we have different situations:

- Nissan, as a first mover, decided early on to engage in cooperation with NEC by creating the Automotive Energy Supply Corporation (AESC) in 2007[13],
- Toyota and Honda, which have been involved in the development of hybrid vehicles for a long time, must now catch-up with competitors on BEVs and engage in cooperation to do so,
- Hyundai has entered into an alliance with LG Chem through its subsidiary Hyundai Mobis and is considering buying from another supplier,
- Lastly, Hozon has concluded a cooperation with CATL.

Since some automakers don't have the same industrial and procurement patterns in all regions of the world, we also present 6 additional different configurations, the analysis of which also provides information on the different strategies of automakers:

- Honda and Ford have signed cooperation agreements with other automakers, respectively GM in USA and VW in Europe, to catch up with the market,
- As far as the Buy cases, we have 4 cases of localization strategies in China to take advantage of the cost of local supply chain: GM, Tesla, Renault and Nissan.

	Design Perimeter			
Automakers	Cell	Module	Battery pack	BMS
BMW	Buy	Make	Make	?
BYD	Make	Make	Make	Make
Daimler	Buy	Make	Make	Design
FCA	Buy	Make or buy ?	Make	?
Ford Mach-E	Buy	Make		?
Ford Europe	Ally with another automaker			
GM USA	Ally	Make	Make	Design
GM China	Buy components and modules matching GM platform specifications			
Honda but USA	Ally with a battery maker elsewhere			
Honda USA	Ally with with another automaker			
Hyundai	Buy	Ally and Buy (in the future)		
Hozon	Ally			
Lucid Motors	Buy	Make		
NIO	Ally	None	Make	
Nissan but China	Ally with a battery maker			Buy
Nissan China	Buy			
Groupe PSA	Buy		Make	?
	After 2023 Ally with a battery maker			?
Renault Group	Buy		Make	Design
Renault Group China	Buy			
Tesla USA	Ally	Make	Make	Design
Tesla China	Buy	Make	Make	Design
Toyota	Ally with tier 1 suppliers and battery makers			
VW	Buy and Ally	Make	Make	?

Table 6: Summary of Make, Buy Ally strategies for HV battery system perimeter

Given the late decision of some car manufacturers to make a definitive commitment to BEV production, which leads to some Ally situations, the observed situation is very close to what we learned from automakers interviews and public statements with a 70% of battery packs make capability and roughly 50% of them (including Honda and Toyota) having a BMS make or design

capability. It is also very much in line with the answer of top executive of automaker1 when we asked if the same decision would be made for the next five years:"*Yes, for the exact same reasons*".

The answer made by top executive from automaker2: "*For the future, we are taking another step forward in interchangeability by specifying standardized cells. We also secure supplies to ensure a production of about 60% of BEVs from the 2030s onwards*" confirms that the struggle for cell volume supply is a real issue. It also points out that some automakers are looking to be increasingly intrusive in cell specifications, and, consequently, move even further outside their historic core design knowledge, to improve BEV performance faster than their competitors.

4.4. Observation of electric powertrain system value chains

4.4.1. Summary of automaker and supplier public statements and executive interviews

Stefan Juraschek, head of Development Electric Powertrain at the BMW Group said: "*When the development plans for the BMW i3 became tangible, there wasn't a single electric motor on the market that would have met all our criteria. And today we are still just as unwilling to make any compromises when it comes to key performance characteristics, such as space requirements, output and weight. Drive systems have always been an area that has set the BMW Group apart from the competition. And exactly the same applies to electric drive systems*[14]."

When asked about the production strategy for the electric powertrain system, top executive of Automaker1 said: "*There are many suppliers of electric motors, but few were able to provide motors that meet the requirements (cost and quality) of the automotive industry. Since the motor operation also has many effects directly felt by the customer (response time, braking, ..) and it was again a good opportunity to control costs and maintain jobs, we manufactured it in-house*." The top executive of Automaker2 remarked: "*With a strong background in electric motor design from previous projects, we have developed unique, cutting-edge technologies to improve the performance of electric motors. We decided to manufacture them because we were the only ones to master these technologies, and it was a good opportunity to learn and progress while maintaining employment".*

When we asked if the same decision would be made for the next five years, the top executive from Automaker2 said: "*We will continue to do so in the future because we see the electric motor as a differentiator and we want to retain an important part of the electric powertrain system value*

chain as well as maintain jobs." On his side, the top executive form Automaker1 implicitly recognizes that the situation could change, mainly for economic reasons: "*In 5 years, yes for the same reasons, but many Tier 1 suppliers are able to scale up. In 10 years, specialized suppliers may be able to outperform OEMs, which could change the decision.*"

4.4.2. Global summary of observations

What we have discovered through interviews with top executives, statements from automakers, and a search of company websites is captured in the summary table below (see Appendix 5 for detailed results). Except for one case of alliance with a specialist supplier, all other automakers do the assembly of the electric powertrain in-house and 70% of them (12/17) have the capability to "make" the e-motor.

	Design Perimeter		
Automakers	E-motor	Gearbox	Electric Powertrain
BMW	Make	Make	Make
BYD	Make	Make	Make
Daimler	Make	Make	Make
FCA	Buy		
Ford USA	Make	Make	Make
Europe	Ally with a automaker		
GM USA	Make	Make	Make
China	Buy (local supply chain according to GM Ultium requirements)		
Honda	Ally	Make	Ally
Hyundai	Make	Make	Make
Hozon			
Lucid Motors	Make	Make	Make
NIO	Make	Make	Make
Nissan	Make	Make	Make
Groupe PSA	Ally	Make	Make
Renault Group	Make	Make	Make
Tesla	Make	Make	Make
Toyota	Make and Ally		
VW AG	Make	Make	Make

Table 7: Summary of make, Buy, Ally strategies for electric powertrain system

We also mention that some of them have concluded alliances with suppliers to quickly catch-up with other competitors such as Toyota, Honda or Groupe PSA. In this specific case, Groupe PSA has recently started the production of electric motor and powertrain in its own factory, located in the eastern region of France, which confirms the technical and economic interests of automakers for the make strategy.

4.5. Summary of observations

We are exploring whether or not the integration of the high-voltage electric battery and electric powertrain into the existing dominant design of a vehicle will trigger a move towards full mirroring in production.

The figure below, which summarizes our observations, brings contemporary evidence, from nearly the entirety of electric vehicle (EV) manufacturing worldwide, that production has, in fact, not changed – or perhaps *not yet* changed. Electric vehicles are being manufacturing in mixed-model production within the existing assembly plants of the world's automakers. Purely electric vehicle manufacturers, such as Tesla, follow a production process that is recognizably the same as how traditional automakers are incorporating EVs into the same assembly lines where they make ICE models.

--- Figure 7 to be included here – see file Figure 7.jpg ---

Figure 7: Observed impacts of electrification on ICEV production system

Furthermore, the sourcing of key components for EVs is also mostly no different from how ICE components are sourced. Engines and powertrains have always been so important to the performance of an automobile that they are vertically integrated by automakers, albeit with suppliers contributing many individual parts. For EVs, while the reliance on batteries as the energy source draws on entirely new types of technical knowledge (electrochemistry more than mechatronics) and battery cells are made by new specialist suppliers, the evidence to date is that the manufacturing of battery packs, the provision of a battery management system (BMS) that governs energy use vis-à-vis depletion and recharging, and the manufacturing of electric powertrains is vertically integrated, despite modularity in the product architecture that would seem to support a much more disintegrated supply chain.

On the one hand, this is perhaps not surprising. EVs constitute only 2-3% of the 65 million personal vehicles sold each year. Automakers have existing assets in the form of manufacturing plants that they seek to leverage and whose capacity they need to fill to remain cost-competitive. Building a separate manufacturing plant – with a new manufacturing process that closely mirrors the modular design of an EV powertrain – is impractical at such low volumes. Even Tesla's first plant is the former NUMMI (GM-Toyota joint venture) plant (and before that a GM plant). As a

startup without profits, it had a strong incentive to adapt its production process to utilize the existing manufacturing assets.

Empirically, we find this happens due to: (i) the importance of the two modules in the overall performance of the vehicle, as perceived by customers; (ii) the difficulty of finding suppliers capable of delivering them to the very demanding conditions of the automotive industry; (iii) the desire to preserve as much of the value of the final product as possible; (iv) an interest in conserving existing and costly assets; and, finally, (v) the possibility of retaining jobs in existing factories when the electric vehicle is known to have a lower manufacturing time.

5. Discussion

Here we discuss our results in light of our research question: “Will a change in dominant design that affects modularity-in-design be mirrored in a corresponding change in modularity-in-production?” or reframed in terms of our characterization of modularity theory, “Will a change in dominant design that boosts MID also lead to increased MIPP or MIPS?” More precisely, our objective is to shed light on "partial mirroring" situations: why do they occur? Are they transitory phases before the advent of more exact alignment? Or, on the contrary, are they stable strategies that explains the resilience of the current production system, despite the misalignment?

We organize the discussion as follows. First, we address the specific context of the transition from ICEVs to EVs in the automotive sector. Second, we consider the general theoretical lessons with respect to the transient or strategic nature of partial mirroring.

5.1. Partial mirroring for EVs: a transitional stage or a perennial strategy?

First we consider the production of full vehicles from a MIPP perspective. We observe that the increased MID of EVs does not change the already-high MIPP for manufacturing of BEVS mixed with ICEVs, in a continuation of fully in-house production.

Yet if the mirroring hypothesis is correct, we should be able to see a different process underway for purely EV companies. However, the manufacturing plants where new pure electric players produce BEVs are designed and operated like conventional ICEV plants. In our mixed model ICEV-BEV production example, we concluded that there is a very strong MIPP to handle the very large diversity of ICE powertrains. This well-established MIPP capability combined with

the fact that automakers have taken advantage of MID to design the electric powertrain themselves leads to an ideal situation for the perpetuation of MIPP methods already in use.

From a short-term perspective, this observation is consistent with (i) the existence of high MIPP in modern manufacturing, regardless of whether MID is high or low, and (ii) the persistence goal, in modern manufacturing, to achieve a design that can be mass produced at low cost. When a top executive from Automaker1 says: "*But once BEVs prevail over EVs, we will have to optimize our manufacturing plants accordingly",* we hear a logic of further rationalization of existing production assets. The elimination of the "engine dress line" (Calias, 2021), per the case study in section 4.1, is an example of an incremental change that doesn't affect the core production process.

Furthermore, the greater modularity of EVs due to high-voltage batteries and electric powertrains, while significant, isn't transformative of final vehicle assembly because so much of the production process *isn't* changed, given that EVs still have all the other functions of a modern vehicle, expected by consumers and required by regulations. We predict that the current MIPP well-established and optimized for ICEVs, will likely persist for a long time, as will in-house production of BEVS.

Second, we consider the issue of whether high-voltage batteries and electric powertrains will be outsourced. These are two new modules that move the dominant design of a vehicle substantially towards high MID – and both involve technical expertise not already widely available at automakers. While we anticipated a high level of outsourcing, the data show that roughly 70% of automakers have a "make" strategy for both modules.

This is consistent with past research on modularity initiatives in the auto industry. The observation of several modularity initiatives pushed by automakers such as Ford, Mercedes-Benz and others, widely heralded as the first automotive modules, didn't really boost MID but rather contributed to MIPP by facilitating modules installation at the final assembly line (Baldwin and Clark, 1997; MacDuffie, 2013).

Observing the effects of Mercedes-Benz's decision, in USA, to outsource the cockpit to Delphi, Baldwin and Clark (1997) point out that this ultimately reduced cost and complexity and freed up space for the automaker. But, fundamentally, the great automotive industry push for MID was not accomplished - partly because of these inherent technical interdependencies and partly to

preserve the OEM's power as a systems integrator and not cede it to mega-suppliers who would assume a greater design role.

Fourcade & Midler's articles (2005, 2004) elaborate on the example of the front end module to reveal why suppliers were ultimately not very enthusiastic about adhering to the automakers' demand for more MID. The added value for suppliers lies in their ability to achieve economies of scale (high volumes) and learning (more frequent redesign rates) through slight customization for each customer. The larger and more complex the module, the more the supplier has to manage specifications specific to each automaker who also wants to control the internal design of the module. As a result, engineering costs increase and the benefits of co-design between the automaker and the supplier decrease.

As the MIPS expectation that outsourcing modules to suppliers would boost MID did not materialize in the recent ICEV-dominated phase of the automotive industry, it is less surprising that we didn't observe outsourcing for high-voltage batteries and e-powertrains even if they have higher MID than the MIPP-optimizing cockpit and front end modules. But given the advantages to learning and capability-building – and potentially competitive advantage -- to the automaker's time-honored "know more than you make" strategy, choosing "make" or "ally" rather than "buy" is a way to maintain the centrality of the automaker's system integrator role – particularly at this early stage of EV scale-up.

What of the long-term sustainability of the production strategies we have observed so far? For example, does the electrification of powertrains contain potential evolutionary properties not yet activated in the designs of current products, which could, in the future, justify more radical transformations of production processes? The modularity literature highlights an ongoing process of modularization for nearly all products as the interdependencies across module boundaries are better understood and interface standardization and "information-hiding" become more feasible. If the MID of high-voltage batteries and electric powertrains rises still higher – along with pressures to reduce costs and complexity -- might we expect a change in "who does what"? The interview data from top executives suggest that they see this as a distinct possibility in the future.

And will the fully-EV assembly plant of the future look radically different from today's well-established template? Tesla, as a newcomer to this industry, is extremely interesting in this regard. Tesla's California plant (in our data) organizes production for its 100% EV model mix in exactly the same way as other companies doing mixed-model ICEV-BEV production. However the legacy

NUMMI plant, as a fixed asset, may have constrained how much Tesla could innovate in production. Tesla now has a new plant in Shanghai and is building new plants in Austin (Texas) and Berlin. The Shanghai plant appears to resemble the California plant very closely; we can see if this pattern continues once the Austin and Berlin plants open.

Concerning the strategy for MIPS, the auto industry has always, after a vertically-integrated or alliance phase during the learning period for a new technology, tended to outsource those components. As far as EV components are concerned, we are still far from this period of stabilization, particularly in the field of batteries. Manufacturers' strategies are driven by two imperatives that do not necessarily converge: securing supplies in a context of exploding demand on the one hand, and maintaining supply flexibility and the ability to negotiate prices in a context of uncertainty about the medium-term evolution of battery performance. The colossal investments[15] made by some manufacturers in mega battery factories based on current technologies (Tesla, VW) are clearly in line with the first imperative. The gamble is that there will be a gap between the immediate need for large capacities and the later availability of solid state batteries, which promise major performance gains compared to liquid electrolyte batteries.

In any case, we do not see why, beyond this undecided medium-term phase, the convergence towards a standardized automotive market for battery **cells** would not take place via the stabilizing of oligopolistic competition. But we can see automakers continuing to want to control the architecture for battery **packs**, in support of flexible configurations to meet the needs of a portfolio of different vehicle sizes, weights, and purposes – and likewise for the software of the battery management system, which does have to deal with the battery's interdependence with the rest of the vehicle's electrical system.

Similarly, in terms of electric powertrains, suppliers may develop capabilities to generate innovative designs and performance thresholds attractive to several manufacturers, allowing them to reach economies of scale. This has happened for vehicle subsystems such as engine control, HVAC, lighting and others. From a competitive point of view, this might shift some value towards suppliers and away from automakers.

But at a strategic level, the question arises whether this reduction in the automaker's share of added value would necessarily reduce their power in the system integrator role atop the value chain. After all, automakers are still very much in control of their supply chains even though they only produce 30 to 45% of the added value internally. Recall two arguments previously advanced

(Jacobides and MacDuffie, 2013; Jacobides, MacDuffie, and Tae, 2015) about how automakers hold onto the dominant share of value in their sector. First, they are legally responsible to customers and governments for meeting regulatory requirements with respect to safety, quality assurance and environmental performance. Second, they have built brand power through sustained long-term marketing, and their brand value depends on them being the guarantors of a certain type – and level – of customer experience and then delivering this.

Electrification has no obvious direct effect on these two dimensions. Automakers will still have the regulatory responsibility for EVs, across safety, quality, and environmental issues, and will still strive to provide a branded customer experience. GM, in connection with its recent pledge to make only EVs by 2035, is saying that the "charging experience" is an essential piller of its overall customer relationship, along with "shopping and buying" and "ownership".

Our conjecture is therefore that the "partial mirroring" situation associated with the major disruption of automotive dominant design during the transition from ICEVs to EVs will persist as a perennial strategy of automakers. We do anticipate evolution as other technological or distribution transformations occur. An interesting research pursuit would be the analysis of the link between these different trajectories, i.e., can electrification be a lever for faster and more efficient digitalization of both the automobile and mobility services? The fact that Tesla is a pioneer in vehicle computerization as well as electrification is a clue. Similarly, the shift from a B2C business model to a B2B model, where the service operator provides the link to the final customer, may cause a break in the value chain, where the operator could more easily combine motors, batteries and bodywork according to a Dell-like model. In both examples, electrification could be an enabler -- but it is not the primary driver of industry transformation.

5.2 General theoretical lessons and research perspectives

To generalize beyond the specificity of the automotive context and EV innovations, we move to sectoral comparison along historical, physical and strategic dimensions, specifically with the IT sector where so much confirmation of the mirroring hypothesis has occurred.

Considering the physical dimension, the automobile is the most heavy and bulky mass consumer durable good. The physical integration of a vehicle brings logistics issues to the forefront, forcing careful consideration of where production of large modules need to be located in relation to the final assembly plant. In contrast, the IT sector integrates high-value but small

and lightweight components such as chips that can be flown around the world when necessary, except when it provides software, which is material-less, i.e. has no physical instantiation.

Historically, the electrification of vehicles comes after a century of rationalization of mass production. In computing, the history is shorter, the evolutionary trajectory is faster (due to Moore's Law's uncanny accuracy as to the rate of improvement in silicon chip performance), and product lifecycle bifurcations are stronger, with the advent of first the PC, then the laptop, then the smartphone. For IT, with so many major architectural ruptures justifying the concomitant introduction of marked ruptures in the production processes, there is little value in maintaining or sustaining a past industrial heritage – if it's even possible.

On the strategy level, the distribution of the actors who bear the weight of the investment to bring a new product to market is very different. In the IT sector, the suppliers of key components (e.g. microprocessors) bear the investment burden. In contrast, in the automotive sector, the automaker (aka the system integrator) assumes the bulk of new product investment costs. This motivates the system integrator to adopt a "reuse" attitude towards the production equipment – and the associated production processes – in order amortize its capital investment.

This brief juxtaposition of these very different contexts shows that whether the mirroring hypothesis -- which posits a isomorphic relationship between the technical interdependences of the product and the organizational arrangements that support design, production, and sale – holds is contingent on variation in these material, historical and strategic dimensions.

Still the fact that multiple studies of the automotive industry find partial mirroring while studies of the IT industry find full mirroring does not only indicate important differences at the sectoral level but also insights into periods of high technical change and uncertainty.

For example, Furlan et al. (2014), in their study in the air conditioning industry, find that a highly modular product architecture is not helpful to understanding the organizational arrangements. They write, "Our results show that the across-firm mirroring hypothesis does not hold for technologically dynamic components. The mirror gets 'misted up' for components characterized by high technological change with buyers and suppliers engaging in 'thick' relationships even in the presence of highly modular components." They take issue with the claim that modular designs have low coordination requirements; indeed, they argue that component modularity reduces the need for interorganizational coordination *only if components are*

technologically stable. Until such a time, system integrators will strive to "know more than they make" (Brusoni et al., 2001) even if this means partial mirroring.

This life cycle perspective fits the EV scale-up case quite well. High-voltage battery systems and e-powertrains are not yet technologically mature, nor is the overall EV architecture. There may yet be innovations that could, in time and after processes of modularization, support a mature EV industry in which well-defined modules, with clearly-specified information-hiding interfaces, are mirrored by a horizontal industry structure dominanted by component specialists. Time will tell.

6. Conclusion and future research

The emerging ecosystem around Electric Vehicles (EVs) – which has a more modular dominant design (i.e. more MID) than traditional ICEVs – now offers enough real-world examples to investigate whether modularity theory's mirroring hypothesis will hold vis-à-vis a corresponding change towards higher MIP. We undertook that investigation by linking our research question to two largely separate literatures: one that stays focused on the product as artifact and how it is designed and produced (we call this modularity-in-production-process or MIPP) and the other that moves to the organizational and industry level of analysis to focus on the boundaries of the firm (make vs. buy), the dynamics of competition, and the industry architecture (we call this modularity-in-production-system or MIPS). We wanted to understand the MID-MIPP and MID-MIPS relationship at an early moment in the scale-up period of the EV life-cycle.

Since MIP has received much less attention than MID, we focused on the question of where the whole EV is produced, i.e., within existing assembly plants of automakers, or in new facilities that pioneer new production methods? We found that nearly 100% of EVs being sold today are produced on mixed-model lines with ICEVs. This was not a huge surprise as the MIPP we observe is most notable for its continuation of mass production methods utilized in the automotive sector for many years now.

We also looked at where and how the two key EV components -- high-voltage batteries and electric powertrains (both of which are much more modular than corresponding components for ICEVs) -- are designed and produced. Here we anticipated outsourcing, given the high level of MID and the availability of specialist component firms eager for contracts. Instead, the level of MIPS does not mirror the level of MID, since automakers are following "make or ally" rather than

"buy" strategies. Probing the recent literature on modularity initiatives in the auto industry, we find this persistant partial mirroring is not unusual. Automakers, as system integrators, are highly motivated by cost and competitiveness pressures as well as long-established routines to keep components vertically integrated (or quasi-integrated via close ties to alliance partners) to amass knowledge and capabilities, particularly in periods of technical advance and uncertainty.

Do our findings mean that EVs will provide "nothing new under the sun," at least from a MIPP and MIPS perspective? The founder of EV startup, Fisker, is pursuing a different production model, akin to consumer electronics, choosing to work with two different contract manufacturers to produce his new vehicle design – Magna (primarily a supplier but also builds certain niche low-volume models for various automakers) and Foxconn (the contract manufacturer of the iPhone, premised on their development of an electric, autonomous, open source platform).

For Fisker, the possibility that EVs will be manufactured in the same type of production system as ICEVs is a sign of an industry stuck in the past. "The auto industry is very stale," he said in a recent interview. "We still talk about adopting the Toyota manufacturing system."[16] We can interpret Fisker's comment as indicating his expectation that the mirroring hypothesis will (and should) hold for EVs, i.e. that the new (modular) design will be mirrored in a new (modular) production system – one that could foretell a future change in industry structure, from vertical to horizontal, as seen in past disruptions of the IT industry.

To date, we have seen no evidence of the trends he predicts. Nor do we have much confidence that Fisker's subcontracting of manufacturing to Magna and Foxconn will yield a innovative new manufacturing paradigm to succeed Toyota Production System. The auto industry operates on a slower clockspeed than the IT industry; its predominantly integral architecture results in complex inter-organizational relationships affected by technical interdependencies in the product architecture; and the system integrator role of automakers puts them in charge of managing these interdependencies and largely in control of their supply chain.

Is this situation transitional or perennial? Since, for EVs, we are still far from a period of stabilization, particularly for batteries, we hypothesize that "partial mirroring" will be a perennial strategy of automakers. The greater modularity of EVs is not a sufficiently overwhelming force to bring about a radical transformation of production – at least not yet!

[1] E.g., Hybrids (HEV), Plug-in Hybrid Electric Vehicles (PHEV), Battery Electric Vehicles (BEV) and Fuel Cell Vehicles (FCV).

[2] https://www.ev-volumes.com/

[3] https://about.bnef.com/blog/electric-vehicle-sales-to-fall-18-in-2020-but-long-term-prospects-remain-undimmed/

[4] As the merger of FCA and Groupe PSA Group to create Stellantis N.V. is very recent, we report separate data for FCA and Groupe PSA.

[5] More precisely, for the BMS we will distinguish between MAKE and DESIGN, i.e. design by an automaker and production by an Electronic Manufacturer Specialist

[6] The description proposed here focuses on the main components, parts and modules and, therefore, is not intended to be an exhaustive list of the materials and processes involved. There may be differences between manufacturers depending on the design choices made but the overall framework proposed is fairly representative of the state of the art.

[7] https://www.daimler.com/products/passenger-cars/mercedes-benz/eq-model-offensive.html

[8] https://www.daimler.com/products/passenger-cars/mercedes-benz/production-eqc.html

[9] https://media.daimler.com/marsMediaSite/en/instance/ko/Expansion-of-the-global-battery-production-network-Mercedes-Benz-Cars-lays-foundation-for-a-battery-factory-at-the-Untertuerkheim-site.xhtml?oid=42972795

[10] https://www.bmwgroup.com/en/elektromobilitaet/production.html

[11] https://www.volkswagenag.com/en/news/2021/03/power-day--volkswagen-presents-technology-roadmap-for-batteries-.html

[12] https://www.alliance-2022.com/news/alliance-ventures-invests-in-enevate-to-advance-li-ion-battery-technology-for-electric-vehicles/

[13] https://www.envision-aesc.com/en/aboutus.html

[14] https://www.bmwgroup.com/en/news/2019/interview-juraschek.html

[15] According to Bosch, roughly 2 billion Euros for 200GWH - https://www.bosch-presse.de/pressportal/de/en/the-go-to-partner-for-electric-driving-boschs-electromobility-strategy-147008.html

[16] https://www.bloomberg.com/news/articles/2021-02-24/apple-partner-foxconn-to-form-ev-partnership-with-fisker?sref=Ipu3VTcG

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7. Appendixes

7.1. Search and Selection Procedure for Data from Company Websites

We searched a wide range of industry-related websites to extract, manually, relevant information about the manufacturing and sourcing of BEVs and their key components, following these search and selection procedures:

1. Search at the English language website of the automaker for general keywords such as "*electric*", "*electromobility*", "*battery*", "*e-motor*", "*electric powertrain*", "*production*",
2. Once a list of appropriate pages is returned, we engaged in an iterative and adaptive search process that required a significant level of expertise in electric vehicles and manufacturing processes. This activity was carried out by the first author, who has more than thirty years of work experience in the engineering division of a global automaker.
3. If the search on the automaker's website does not give all the expected results, we proceed to an open google search for the missing result(s). We then use the key sentences - depending upon the missing result(s) -: "*where is produced the vehicle X from automaker Y?*", "*what are the high voltage battery suppliers for the automaker Y?*", "*what are the e-motor (or electric powertrain) suppliers for the automaker Y?*" and apply the specific and iterative process, described above, to the pages returned.
4. For the specific case of announcements from one company that mention another company, i.e. a press release announcing cooperation, a procurement contract, etc., we always connected to the official website of the mentioned company to confirm accuracy and obtain additional data. Other triangulation steps were taken as necessary to have confidence in the data, particularly multiple sources when available.
5. The sources of the collected data are stored in a "Sources of data" spreadsheet whose template is provided in Table 8. For each automaker and for each unit of analysis (EV production, Battery system value chain, electric powertrain value chain), we capture are URL/website address(es) of the accessed website(s); the keyword(s) used in the search; the version date of the information (if this was indicated on the visited page; otherwise "*none*"); and the date of access.
6. **(T)** for "**T**riangulated data" is indicated, as appropriate, for data in the summary tables.

Automaker	Unit of analysis	Sources of data			
		Access keyword(s)	Website address	Date of edition	Date of access

Name of automaker	Production of EVS				
	Battery system value chain				
	Electric powertrain value chain				

Table 8: Template of the table "Sources of data"

7.2. Sources of data table

Automaker	Unit of analysis	Sources of data			
		Keyword(s) to access	Website address	Date of edition	Date of access
BMW	Production of EVS	*Company site, Electromobility then production* *News site, Electromobility, production network of the future* *News site, Production of BMW iX3*	https://www.bmwgroup.com/en/elektromobilitaet/production.html https://www.bmwgroup.com/en/news/2021/produktionsnetzwerk.html https://www.press.bmwgroup.com/global/article/detail/T0318114EN/start-of-production-for-fully-electric-bmw-ix3?language=en	None 18/02/2021 01/10/2020	17/03/2021
	Battery system value chain	Same sites as above Plus *News site, battery cell*	https://www.press.bmwgroup.com/global/article/detail/T0311274EN/bmw-group-continues-to-drive-electromobility:-long-term-supply-contract-with-northvolt-for-battery-cells-from-europe-concluded	16/07/2020	
	Electric powertrain value chain	Same two first sites as above			
BYD	Production of EVS	*BYD site, select news site and search for EV launches*	https://www.byd.com/en/news/2020-07-14/BYD%27s-flagship-Han-EV-series-officially-goes-on-sale-New-EV-series-is-BYD%27s-flagship-offering-for-the-global-luxury-sedan-segment http://autonews.gasgoo.com/new_energy/70017729.html	14/07/2020 13/11/2020	17/03/2021
	Battery system value chain	*BYD site, select Innovation at BYD, Battery innovation*	https://www.byd.com/en/InnovationByd.html	None	
	Electric powertrain value chain				
Daimler	Production of EVS	*Electric production network. Six new EQ models*	https://www.daimler.com/products/passenger-cars/mercedes-benz/eq-model-offensive.html	2021 Daimler AG. All Rights Reserved	25/03/2021
	Battery system value chain	*Global battery production network* *Electric Mobility*	https://www.daimler.com/innovation/case/electric/battery-cells.html https://www.daimler.com/company/locations/battery-factory-jawor.html https://www.daimler.com/innovation/digitalisation/industry-4-0/battery-production-hedelfingen.html	23/03/2021	
		Innovation, Drive systems, electric	https://www.daimler.com/innovation/case/electric/battery-cells.html https://www.daimler.com/innovation/drive-systems/electric/mercedes-benz-catl-battery.html https://www.daimler.com/innovation/drive-systems/electric/mercedes-benz-and-farasis.html	05/08/2020 03/07/2020	
	Electric powertrain value chain	*Electric Drive*	https://www.daimler.com/company/locations/campus-untertuerkheim.html	05/03/2021	
FCA	Production of EVS		https://www.fcagroup.com/en-US/media_center/fca_press_release/2019/february/pages/fca_to_expand_production_capacity_in_michigan.aspx https://www.fcagroup.com/en-US/media_center/fca_press_release/2018/november/Pages/meeting_between_FCA_and_trade_unions_in_turin.aspx	26/02/2019 29/11/2018	18/03/2021

	Battery system value chain		https://www.media.stellantis.com/em-en/corporate-communications/press/new-battery-hub-at-mirafiori-speeds-fca-electric-product-plans	22/10/2019	
	Electric powertrain value chain	*Google search" e-motor supplier for fiat 500"*	https://en.wikipedia.org/wiki/Fiat_New_500		
Ford	Production of EVS	*Google search "production Mustang Mach-E" Newsroom tag "Mustang Mach-E" Newsroom tag "manufacturing"*	https://fordauthority.com/2021/02/2021-ford-mustang-mach-e-sales-and-production-numbers-show-quick-ramp-up/ https://fordauthority.com/2020/11/ford-mustang-mach-e-production-requires-loads-of-new-tech/ https://media.ford.com/content/fordmedia/fna/us/en/news/2021/01/27/ford-manufacture-mustang-mach-e-china.html https://media.ford.com/content/fordmedia/fna/us/en/news.search.manufacturing.0.10.0.0.country.htmlhttps://media. https://media.ford.com/content/fordmedia/fna/us/en/news/2020/11/09/ford-kansas-city-all-electric-ford-e-transit.html https://www.fordotosan.com.tr/en/investors/at-a-glance/vehicle-production	04/02/2021 06/11/2020 27/01/2021 17/02/2021 10/11/2020	22/03/2021
	Battery system value chain	*Google search "what are the HV battery suppliers for Ford?"*	https://www.evspecifications.com/en/news/01402da https://skinnonews.com/global/archives/1237 https://www.wsj.com/articles/gm-ford-need-electric-car-batteries-but-take-different-paths-to-get-them-11601717403	27/05/2020 26/06/2020 03/10/2020	
	Electric powertrain value chain				
GM	Production of EVS	*Newsroom, tag "battery cells"*	https://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2020/oct/1020-event.html https://plants.gm.com/media/us/en/gm/ev.detail.html/content/Pages/news/us/en/2020/oct/1016-event.html https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2019/mar/0322-orion.html	20/10/2020 16/10/2020 22/03/2019	19/03/2021
	Battery system value chain	*Newsroom tag "electrification"*	https://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2021/feb/0219-ultium.html https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2020/sep/0909-wbms.html https://media.gm.com/media/cn/en/gm/news.detail.html/content/Pages/news/cn/en/2020/Aug/0819-gm-tech-day.html	19/02/2021 09/09/2020 19/08/2020	
	Electric powertrain value chain		https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2020/sep/0916-ultium-drive.html	16/09/2020	
Honda	Production of EVS	*News, search for Battery electric vehicle Google search "production of Honda e"*	https://global.honda/newsroom/news/2020/c200403eng.html https://en.wikipedia.org/wiki/Honda_e	03/04/2020 none	19/03/2021
	Battery system value chain	*News search for batteries* Google search " what is the battery supplier for honda e?"	https://global.honda/newsroom/news/2020/c200710eng.html https://insideevs.com/news/354522/honda-e-dedicated-ev-platform-35-5-kwh-battery/	10/07/2020 13/06/2019	
	Electric powertrain value chain	*News search for electric vehicle motor*	https://global.honda/newsroom/news/2017/c170703beng.html	03/07/2017	
Hyundai	Production of EVS	*Newsroom, tag production of Kona electric*	https://www.hyundai.news/eu/model-news/hyundai-starts-delivery-of-kona-electric-produced-in-czech-republic/ https://en.wikipedia.org/wiki/Hyundai_Kona https://en.wikipedia.org/wiki/Hyundai_Ioniq	13/03/2020	23/03/2021

		Google search "where is produced Kona electric / Ioniq?"			
	Battery system value chain	*Google search "Hyundai battery cell supplier"* *Google search "Hyundai battery pack supplier"*	https://electrek.co/2021/02/23/hyundai-taps-catl-and-sk-innovation-to-supply-more-batteries-for-e-gmp/ http://www.businesskorea.co.kr/news/articleView.html?idxno=62198 http://eng.skinnovation.com//business/battery.asp https://english.etnews.com/20210223200001	23/02/2021 12/03/2021 None 23/02/2021	
	Electric powertrain value chain	*Google search "Hyundai electric motor supplier"*	https://www.reuters.com/article/us-hyundai-mobis-diversification-idUSKBN25L029	24/08/2020	
Hozon	Production of EVS	*Company website* *Google search "hozon manufacturing plant"*	https://www.hozonauto.com/en/brand.html http://autonews.gasgoo.com/china_news/70016469.html	None 22/01/2019	22/03/2021
	Battery system value chain	*Google search "Hozon battery supplier"*	https://www.chinapev.com/ev-2/hozon/hozon-auto-and-catl-to-deepen-battery-cooperation/	04/03/2020	
	Electric powertrain value chain				
Lucid Motors	Production of EVS	*exhaustive analysis of newsroom* *Google Search "Lucid motors battery supplier"*	https://www.lucidmotors.com/media-room/lucid-motors-completes-construction-on-first-greenfield-electric-vehicle-factory-in-north-america/	01/12/2020	19/03/2021
	Battery system value chain		https://www.lucidmotors.com/media-room/lucid-motors-announces-partnership-lg-chem-secures-battery-cells-long-term-volume-production/ https://www.lucidmotors.com/media-room/lucid-motors-proprietary-electric-drivetrain-technology-powers-record-setting-performance/	24/02/2020 02/09/2020	
	Electric powertrain value chain		https://www.forbes.com/sites/markewing/2020/11/19/lucid-motors-creates-the-worlds-most-advanced-battery-electric-car-a-conversation-with-ceo-peter-rawlinson/	19/11/2020	
NIO	Production of EVS	*exhaustive analysis of newsroom*	https://www.nio.com/blog/making-nio-es6-hefei	08/07/2020	19/03/2021
	Battery system value chain	*Google search "battery suppliers for NIO"*	https://www.nio.com/news/nio-launches-100-kwh-battery-flexible-battery-upgrade-plans https://eu.detroitnews.com/story/business/autos/2020/10/27/teslas-chinese-battery-supplier-boosts-profit-pandemic-eases/3745886001/ https://www.ft.com/content/7f0c51e2-26cb-11e8-b27e-cc62a39d57a0 https://fintel.io/doc/sec-nio-nio-ex81-2020-may-14-18396-878	06/11/2020 27/10/2020 13/03/2018 14/05/2020	
	Electric powertrain value chain	*Google search "e-motor suppliers for NIO"*	http://www.xptglobal.com/en/news/the-2020-electric-drive-system-delivery-report-card-is-released.html https://fintel.io/doc/sec-nio-nio-ex81-2020-may-14-18396-878 https://www.automotiveworld.com/news-releases/punch-powertrain-xpt-sign-joint-venture-agreement-production-electric-powertrains/	05/01/2021 14/05/2020 12/03/2021	
Nissan	Production of EVS	*Company site, Towards carbon neutrality, products, Nissan models, electric vehicles* *Google search" where is produced nissan Ariya"*	https://global.nissannews.com/en/releases/release-ed7b0014763a42e1693c5c954e1b7e81-180827-01-e https://global.nissannews.com/en/releases/production-of-new-nissan-leaf-to-begin-in-us-and-uk?source=nng&lang=en-US&rsshttps://en.wikipedia.org/wiki/Nissan_Ariya	27/08/2018 07/09/2017	24/03/2021

	Battery system value chain	*Google search "Nissan leaf battery supplier"* *Google search "what is the supplier of nissan leaf bms"*	https://www.envision-aesc.com/en/aboutus.html https://www.bloomberg.com/news/articles/2019-04-15/nissan-leaf-s-battery-supplier-builds-first-china-factory https://cleantechnica.com/2018/05/12/nissan-renault-make-battery-deal-with-catl-worlds-largest-battery-manufacturer/ https://www.chinapev.com/dongfeng/venucia/dongfeng-venucia-launched-its-first-ev-venucia-d60ev-with-range-of-298miles/ Everlasting report 6.1 https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b0a8fe79&appId=PPGMS	None 15/04/2019 12/05/2018 03/09/2019	
	Electric powertrain value chain	Company siet search "electric powertrain"	https://www.nissan-global.com/EN/PLANT/YOKOHAMA/	None	
Groupe PSA	Production of EVS	*Google search PSA "electricfication strategy"* *Newsroom search "electric vehicle"*	PDF "Electrification strategy" https://archives-media.stellantis.com/en/groupe-psa-strengthens-its-electric-offensive-new-evmp-platform-electric-vehicle-modular-platform https://archives-media.stellantis.com/en/groupe-psa-poissy-plant-produce-additional-vehicle https://archives-media.stellantis.com/en/groupe-psa-wins-2021-%C2%AB-international-van-year-%C2%BB-ivoty-award-its-new-generation-all-electric-compact	01/04/2020 029/07/2020 20/02/2019 17/12/2020	22/03/2021
	Battery system value chain	*Newsroom search "battery cells supplier"* *Google search "PSA battery supplier"*	https://archives-media.stellantis.com/en/groupe-psa-and-total-create-automotive-cells-company-joint-venture-dedicated-manufacture-batteries https://www.electrive.com/2018/05/12/catl-to-deliver-cells-for-nissan-and-renault/ https://www.electrive.com/2019/06/17/psa-sets-up-battery-production-in-slovakia/ https://www.electrive.com/2019/11/29/psa-plant-near-saragossa-will-also-assemble-battery-packs/	03/09/2020 04/05/2018 17/06/2019 29/11/2019	
	Electric powertrain value chain	*Newsroom search "electric motor"*	https://archives-media.stellantis.com/en/%E2%80%9Cnidec-psa-emotors%E2%80%9D-joint-venture-created-groupe-psa-and-nidec-starts-design-its-future-electric	22/05/2018	
Renault group	Production of EVS	*Direct access on website News site, tag twingo, ZOE,press kit electric vehicles* *Google search "where is produced Dacia Spring?"*	https://group.renault.com/en/news-on-air/news/maubeuge-the-alliances-centre-of-lcv-excellence/ https://en.media.groupe.renault.com/news/the-new-twingo-z-e-more-than-ever-the-queen-of-the-city-b897-989c5.html https://group.renault.com/en/news-on-air/news/france-becomes-a-centre-of-excellence-for-renaults-electric-vehicles-within-the-alliance/ https://en.media.groupe.renault.com/s2?query=ZOE%20press%20kit https://en.wikipedia.org/wiki/Dacia_Spring	12/02/2021 24/02/2020 14/06/2018 27/09/2012 None	19/03/2021
	Battery system value chain	*Google search "battery suppliers for Renault"*	https://europe.autonews.com/automakers/renault-worries-about-battery-supplies-growing-ev-market https://cleantechnica.com/2018/05/12/nissan-renault-make-battery-deal-with-catl-worlds-largest-battery-manufacturer/ https://www.argusmedia.com/news/1884902-sunwoda-to-supply-ev-batteries-to-renaultnissan	22/01/2019 12/05/2018 15/04/2019	
	Electric powertrain value chain	*Company website, tag electric motor production*	https://group.renault.com/en/news-on-air/news/renaults-cleon-plant-the-groups-technological-showcase/	22/06/2018	
Tesla	Production of EVS	*Gigafactory berlin*	https://www.tesla.com/gigafactory-berlin	None	20/03/2021
	Battery system value chain	*Gigafactory* *Google search "battery suppliers for Tesla"*	https://www.tesla.com/gigafactory https://www.tesla.com/blog/panasonic-and-tesla-sign-agreement-gigafactory https://www.reuters.com/article/tesla-batteryday-suppliers-stocks-int-idUSKCN26E03G	None 30/072014 23/09/2020	

	Electric powertrain value chain	*Gigafactory*	https://www.tesla.com/gigafactory		
Toyota	Production of EVS	*Newsroom tag electric, search for battery electric vehicle* *IZOA FAW Toyota*	https://global.toyota/en/newsroom/corporate/32126024.html?_ga=2.178284196.1241931722.1616093810-1649816162.1614111812 https://global.toyota/en/newsroom/lexus/30609957.html?_ga=2.139108787.1241931722.1616093810-1649816162.1614111812 https://newsroom.lexus.eu/all-electric-ux-300e-heralds-new-milestone-in-lexus-silent-revolution/ https://global.toyota/en/newsroom/toyota/27769546.html?_ga=2.173033891.1241931722.1616093810-1649816162.1614111812 https://global.toyota/en/newsroom/corporate/22325409.html?_ga=2.210257301.1241931722.1616093810-1649816162.1614111812 https://www.marklines.com/en/news/239226	02/04/2020 22/11/2019 15/06/2020 16/04/2019 25/04/2018 13/05/2020	18/03/2021
	Battery system value chain	*Newsroom tag electric, search for battery*	https://global.toyota/en/newsroom/corporate/31477926.html?_ga=2.206716947.1241931722.1616093810-1649816162.1614111812 https://global.toyota/en/newsroom/corporate/28913488.html?_ga=2.219259929.1241931722.1616093810-1649816162.1614111812	03/02/2020 17/07/2019	
	Electric powertrain value chain	*Newsroom tag electric, search for electric, CASE* *Google search "electric motor supplier for Toyota"*	https://global.toyota/en/newsroom/corporate/30977776.html?_ga=2.131340623.1971602286.1583074634-1551232268.1583074634 https://global.toyota/en/newsroom/corporate/28818821.html?_ga=2.174130466.1241931722.1616093810-1649816162.1614111812 https://global.toyota/en/newsroom/corporate/33344322.html?_ga=2.182520870.1241931722.1616093810-1649816162.1614111812 https://www.thedrive.com/tech/27790/toyota-gears-up-to-become-global-ev-systems-supplier https://www.globenewswire.com/news-release/2020/06/03/2043202/0/en/Toyota-has-a-huge-presence-in-the-Japanese-market-and-an-in-house-motor-production-facility-which-covered-a-significant-share-of-the-market-studied-in-2019.html https://www.toyota-tsusho.com/english/press/detail/190315_004346.html	10/12/2019 10/07/2019 31/07/2020 02/05/2019 03/06/2020 15/03/2019	
Volkswagen	Production of EVS	*Electromobility Volkswagen to manufacture electric cars on three continents* *ID production*	https://www.volkswagenag.com/en/news/stories/2019/01/volkswagen-to-manufacture-electric-cars-on-three-continents.html https://www.volkswagen-newsroom.com/en/stories/e-car-production-for-the-world-6792	29/01/2021	18/03/2021
	Battery system value chain	*Battery system* *Battery cell supplier* *Power day* *Google search "BMS supplier for Volkswagen"*	https://www.volkswagenag.com/en/news/2019/12/key-components-for-a-new-era--the-battery-system.html https://www.volkswagenag.com/en/news/stories/2018/10/powerful-and-scalable-the-new-id-battery-system.html https://www.volkswagenag.com/en/news/2018/11/volkswagen-nominates-further-battery-cell-supplier.html https://www.volkswagenag.com/en/news/2019/06/VW_Group_Northvolt.html https://www.volkswagenag.com/en/news/stories/2021/03/curtain-up-for-power-day.html https://media.nxp.com/news-releases/news-release-details/volkswagen-adopts-nxp-battery-management-solutions-its-meb	05/12/2019 10/2018 12/11/2018 12/06/2019 15/03/2021 20/10/2020	

	Electric powertrain value chain	*e-motor, electric drive*	https://www.volkswagenag.com/en/news/stories/2019/01/once-a-combustion-engine-producer-now-electricity-pioneer.html https://www.volkswagen-newsroom.com/en/press-releases/production-of-electric-drives-begins-in-china-6608 https://www.volkswagenag.com/en/news/stories/2018/09/electric-motor-now-in-series-production-in-gyoer.html https://www.audi-mediacenter.com/en/press-releases/audi-hungaria-produces-e-motors-for-future-ppe-model-generation-13713	16/11/2020 09/02/2021 None 02/09/2021	

The Stellantis website does not include information on vehicle electrification. It is necessary to access the unmaintained FCA archives without search function. Line by line analysis of press releases between 2014 and 2021

7.3. Observation of vehicle production system

Automaker	Vehicle	Assembly plant	Use of standard assembly process	Process modification reusing ICEV dominant design rules	Type of process
BMW	I3	Leipzig (Germany) Existing	No	No	*specific process (1)*
	Mini Electric	Oxford (England) Existing	Yes	Yes	*adapted standard process (2)*
	iX3	BMW Brilliance Automotive in Shenyang, China Existing	Yes	Yes	
BYD	Han EV	Shenzen China **(T)**	Yes[xvii]	Yes	*Adapted standard process (1)*
Daimler	Smart ForFour ED	Novo Mesto (Slovenia)	Yes	Yes	*adapted standard process (8)*
	EQC (X)	Bremen (EQC, EQE), Rastatt (EQA), Sindelfingen (EQS) (Germany) Vitoria (EQV) Spain Kecskemét (EQB) (Hungary) Tuscaloosa EQE, EQS (USA) BBAC (EQC, EQA, EQB) China Existing	Yes	Yes	
FCA	New 500 BEV	Mirafiori (Italy) Existing	Yes	Yes	*adapted standard process (2)*
	New Jeep BEV	Detroit (USA) Existing	Yes	Yes	
Ford	Next generation BEV	Flat Rock Assembly plant (Michigan USA)	Yes	Yes	*adapted standard process (6)*
	Mustang Mach-E All future electric performance SUV	Cuautitlan plant (Mexico) Existing	Yes	Yes	
	Future E-Transit	Kansas City Plant (USA) Existing Gölcük plant (Turkey) Existing	Yes	Yes	
	Future F-150	Dearbon plant (USA) Existing	Yes	Yes	
	All future European EV	Cologne plant (Germany) Existing	Yes	Yes	
GM	Bolt / New BEV	Orion Assembly plant (Michigan USA)	Yes	Yes	*adapted standard process (3)*
	Electric Cadillac	Spring Hill, (Tennessee USA) Existing	Yes	Yes	
	All electric trucks and SUV including GM Hummer EV	FACTORY 0 Detroit-Hamtramck (Michigan USA) Existing	Yes	Yes	
Honda	Everus VE-1	Guangzhou Plant Guandong Province (China) Existing	Yes	Yes	*adapted standard process (2)*
	Honda e	Saitama Factory – Yorii plant Existing	Yes	Yes	
Hozon	Nezha U Nehza N01	Tongxiang (China) Yichun (China) Greenfield	Yes	Yes	*Greenfield plants with adapted standard process (2)*
Hyundai / Kia	Hyundai Ioniq electric	Ulsan (Korea) Existing	Yes	Yes	*Adapted standard process (4)*

	Hyundai Kona Electric **(T)**	Ulsan (Korea) Existing Nošovice (Czech Republic) Existing	Yes	Yes	
	Kia Soul EV	Gwangju (Korea) Existing	Yes	Yes	
	Kia E-Niro	Hwaseong (Korea) Existing	Yes	Yes	
Lucid Motors	Lucid Air	Casa Grande (Arizona USA) Greenfield	Yes	Yes	*Greenfield plant with adapted standard process (1)*
NIO	ET7, EC6, ES8, ES6	NIO-JAC advanced manufacturing center (Hefei China) Greenfield	Yes	Yes	*Greenfield plant with adapted standard process (1)*
Nissan	New LEAF	Oppama (Japan) Sunderland (GB) Smyrna (TE USA) Existing	Yes	Yes	*adapted standard process (6)*
	Silphy Zero Emission / Venucia D60 EV	Huadu (China) Existing	Yes	Yes	
	Ariya	Tochigi (Japan) Existing	Yes	Yes	
	E-NV 200	Barcelona (Spain) Existing	Yes	Yes	
Groupe PSA	e-208	Trnava (Slovakia) Existing	Yes	Yes	*adapted standard process (6)*
	DS3 crossback New Opel SUV	Poissy (France) Existing	Yes	Yes	
	Electric version Opel Astra	Russelsheim (Germany) Existing	Yes	Yes	
	e-Corsa	Zaragossa (Spain) Existing	Yes	Yes	
	e-2008	Vigo (Spain) Existing	Yes	Yes	
	4 electric Vans	Hordain (France) Existing	Yes	Yes	
Renault	Twizy	Busan (Korea) Existing	No	No	*specific process (1)*
	Kangoo 2 (and 3) ZE	Maubeuge (France) Existing	Yes	Yes	*adapted standard process (5)*
	ZOE	Flins (France) Existing	Yes	Yes	
	Renault City K-ZE / Dacia Spring	Shiyan (Hubei – China) Existing	Yes	Yes	
	Twingo ZE	Novo Mesto (Slovenia) Existing	Yes	Yes	
	New BEVs on CMF-EV platform	Douai (France) Existing	Yes	Yes	
Tesla	All models (S, X, Y and 3)	Freemont CA USA Existing	Yes	Yes	*adapted standard process (3)*
	Model 3, Model Y	Shanghai China Greenfield	Yes	Yes	
	Model Y	Berlin Germany (future) Greenfield			
Toyota	Lexus UX300e	Kyushu (Miyata) Japan Existing	Yes	yes	*adapted standard process (3)*
	IZOA FAW Toyota	Tianjin (China) Existing	Yes	yes	
	C-HR GAC Toyota	Guangzhou (China) Existing	Yes	yes	
VW AG	Audi e-Tron	Brussels (Belgium) Existing	Yes	Yes, mixed with ICEVs at launch	*adapted standard process (1)*

	ID3,4 and other vehicles on MEB	Zwickau, Dresden, Emden, Hanove (Germany) Mladá Boleslav, (Czech republic) Chattanooga (USA), Anting, Foshan (China) Existing	Yes	Yes	*adapted standard process (8)*

Supprimé: ¶

7.4. Observation of Battery system value chain

	Design Perimeter			
Automakers	Cell	Module	Battery system	BMS
BMW	Buy CATL, Samsung SDI, Northvolt	Make	Make 3 battery factories in Dingolfing (Germany), Spartanburg (USA) and Shenyang (China)	
BYD	Make	Make	Make	Make
Daimler	Buy SK Innovation, LG Chem, CATL Ally Farasis	Make	Make 9 battery factories in Kamenz (2) Stuttgart-Untertürkheim (2) Sindelfingen (Germany) Jawor (Poland) Beijing (China), Bangkok (Thailand), Tuscaloosa (USA)	In house Design
FCA	Buy	Make or buy?	Make Mirafiori plant (Italy)	
Ford	Buy LG Chem (Wroclaw plant Poland)	Make	Make Mustang Mach-E	
	Europe : Ally VW MEB platform			
GM	Ally LG (USA) LLC plant in Ohio	Make	Make	In house Design
	China : Buy, local supply chain for Ultium platform and drives components			
Honda	Buy Panasonic cells (Honda e)			
	Ally CATL for future supplies in China *56 GWh of lithium-ion EV batteries before 2027*			
	US market : Ally with GM (Ultium platform)			
Hyundai	Buy LG CHEM current vehicles New E-GMP platform : BYD, CATL, SK Innovation **(T)**	Ally HL Green Power (JV Hyundai Mobis and LG Energy Solution), Buy Sebang Global Battery		
Hozon	Ally CATL			
Lucid Motors	Buy LG CHEM	Make (Atieva, Lucid motors technology division)		In house Design
NIO	Buy CATL **(T)** - NIO mentions the use of CTP technology only provided by CATL at the time being	None CTP technology	Make XPT (Nanjing) Energy Storage System Co., Ltd. (NIO subsidiary)	In house Design
Nissan	Ally AESC			Buy Calsonic kansei (now Marelli)
	China: Buy CATL			
Groupe PSA	Buy CATL		Make	

	After 2023	Ally Automotive Cells Company (JV PSA – Saft)	Trnava (Slovakia) Vigo (Spain) Zaragossa (Spain)	
Renault Group	Buy LG Chem (ZOE), CATL (New Kangoo)		Make Flins plant (France) for ZOE, Maubeuge plant (France) for Kangoo	In house Design
	Buy Sunwoda (KZE in China)			
Tesla	Buy Panasonic	Make Gigafactory 1 (Sparks Nevada USA)		In house Design
	Buy LG Chem, CATL	Make Gigafactory 3 (Shanghai China)		
Toyota	Ally with Panasonic in Prismatic batteries			
	Ally with CATL (vehicles produced in China)			
VW	Buy Europe : LG Chem, Samsung and SKI (from 2019) North America : SKI (from 2022) China: CATL (from 2019) Ally Europe : Northvolt In Europe 6 gigafactories 240GWH cells production by the end of 2020 decade	Make	Make Brunswick plant (2019) Salzgitter plant (2024)	?

7.5. Observation of e-powertrain system value chain

	Design perimeter		
Automakers	E-motor	Gearbox	Electric Drive
BMW	Make Landshut plant (Germany)	Make	Make Dingolfing plant (Germany)
BYD	Make	Make	Make
Daimler	Make	Make	Make Stuttgart-Untertürkheim plant (Germany)
FCA	FIAT new 500 : Buy GKN Automotive G400 IPMS		
Ford	Make : Van Dyke Transmission Plant (USA)		
	Europe : Ally VW MEB platform		
GM	USA: Make Ultium drive – production in powertrain plants		
	China : Buy, local supply chain for Ultium platform and drives components		
Honda	But US market, Ally Hitachi Automotive Systems		
	US market : Ally with GM (Ultium platform & drive)		
Hyundai	Make (Hyundai Mobis subsidiary of Hyundai)		
Hozon			
Lucid Motors	Make - Atieva, Lucid motors technology division		
NIO	Make - XPT (Nanjing) E-Powertrain Technology Co., Ltd., NIO subsidiary **(T)**		
Nissan	Make (Yokohama plant)		
Groupe PSA	e-motor Ally Design Nidec PSA JV, make Tremery plant (France) e-transmission Ally Punch Powertrain PSA JV	Make	Make Tremery plant (France)
Renault Group	Europe : Make Cleon plant (France)		
	China : buy		
Tesla	Make	Make	Gigafactory (Sparks, Nevada USA)
Toyota	Make (HEV, PHEV, BEV?) and Ally (components, power control, e-motor)		
VW AG	Make Rotor and stator Salzgitter plant (Germany)	Make	Make For MEB : Kassel plant (Germany), Tianjin Plant (China) Győr Plant (Hungaria) for Premium Platform Electric