Industrial and Corporate Change, 2023, **32**, 129–154
DOI: https://doi.org/10.1093/icc/dtac049
Advance access publication date: 30 November 2022
Original Article

OXFORD

Exploring the structure of internal combustion engine and battery electric vehicles: implications for the architecture of the automotive industry

Johann Peter Murmann*,‡ and Benedikt Alexander Schuler‡

Institute of Management and Strategy, University of St.Gallen, Dufourstrasse 40a, St. Gallen 9000, Switzerland. e-mail: j.peter.murmann@unisg.ch

‡These authors contributed equally to this work.
*Main author for correspondence.

Abstract

How will the technological shift from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs) change the architecture of the automotive industry? To explore this question, we systematically compare the technological structure of ICEVs and BEVs using data from large incumbent automobile companies and start-ups. While our analysis based on technical descriptions and design structure matrices suggests that the power train of BEVs is structurally simpler compared to the power train of ICEVs, BEVs are slightly less modular than ICEVs. We discusss important strategic implications of this finding for incumbent firms and start-ups.

JEL classification: M13, O30

"Battery electric vehicles are more modular than combustion engine vehicles."
Guenther Schuh, founder of BEV start-up e.Go

1. Introduction

In their influential paper, "Agency, structure, and the dominance of OEMs: Change and stability in the automotive sector," Jacobides *et al.* (2016) report a fascinating historical detail: Industry experts predicted in the early 1990s that the architecture of the automotive industry, which describes the division of labor and the distribution of economic value, would evolve like the computer industry. In the personal computer industry, the distribution of economic value shifted from system integrators (e.g., IBM, Compaq, and Dell) to suppliers of the core modules (i.e., Microsoft, which made the operating system, and Intel, which made the microprocessors) when the structure of the personal computer became modular (Baldwin and Clark, 2000). As the development in the computer industry was so prominent, and the automotive industry was regarded as structurally similar to the computer industry, some industry observers predicted that the structure of automobiles would also become more modular, and consequently, the economic value would migrate from the original equipment manufacturers (OEMs) that are the system integrators of automobiles (Ford, General Motors, and Volkswagen, etc.) to the suppliers of core modules.[1]

But the OEMs have continued to capture the lion's share of the economic value in the automotive industry manufacturing internal combustion engine vehicles (ICEVs) through the current period, even though most parts of ICEVs are manufactured by suppliers (Jacobides and MacDuffie, 2013). Subsequent research offered a seemingly conclusive explanation for this observation: OEMs capture the lion's share of economic value in the automotive industry manufacturing ICEVs because they have an architectural advantage (Jacobides *et al.*, 2006).

Although many capabilities contribute to OEMs' architectural advantage in the ICEV era (Jacobides *et al.*, 2016), we argue that it is mainly rooted in three capabilities: First, prior research showed that OEMs' system integrator role represents "their primary source of control over value creation and capture" in the automotive industry (Jacobides *et al.*, 2016: 1944). We refer to OEMs' system integration capabilities as those capabilities that enable them to combine all parts of the automobile and assemble the final product. These capabilities allow OEMs to consider the dependencies between design parameters like the engine, transmission, drive dynamics, thermal operating conditions, interior proportions, and exterior proportions when designing and manufacturing automobiles to create the desired driving experience. Design parameters represent the elements of a technology that describe its various tangible and intangible characteristics.

Second, prior research suggests that "because [OEMs] maintained proprietary component designs, they were able to shape their [industry architecture]" (Jacobides *et al.*, 2016: 1944). Jacobides *et al.* (2016) describe OEMs' design, supply chain, and manufacturing capabilities in the ICEV era under the general umbrella of system integration without distinguishing among the components or subsystems being integrated. Based on other work indicating that core subsystems of technologies are more important than non-core subsystems of technologies (Tushman and Murmann, 1998; Murmann and Frenken, 2006) and interviews with industry engineers suggesting that many components and production processes related to the power train are proprietary, we view OEMs' power train design capabilities allowing them to design and build the most valuable parts of the power train as an important element contributing to their architectural advantage in the automotive industry of the ICEV era. The power train is a key first-order subsystem of automobiles consisting of the engine and the drivetrain. As the power train is closely linked to other design parameters of automobiles, such as the acceleration, speed, and drive dynamics, it is key to creating the desired driving experience. This also makes the integration tasks related to the power train more significant than others.

Third, prior work demonstrated that "OEMs' ownership of regulatory accountability and legal liability gave them significant power to discipline the rest of the sector" (Jacobides *et al.*, 2016: 1944). OEMs can assume the regulatory accountability and legal liabilities regarding the entire automobile in the ICEV era because they developed the capability to certify the quality of the parts, emission standards, and crash safety level to ensure the safe operation of automobiles that is compliant with environmental protection regulations. As legislators impose strong legal requirements on automobiles that must be fulfilled to sell automobiles, OEMs' legal and certification capabilities further contribute to their architectural advantage.

While OEMs' legal and certification capabilities[2] allowed them to fulfill regulatory requirements, it is their power train design and system integration capabilities that enabled OEMs to solve the technical bottlenecks of ICEVs: the power train and integration of the automobile.

1 Jacobides *et al.* (2016) also report the interesting detail that "IMVP researcher Daniel Whitney observed the ubiquity of two books, Clayton Christensen's (1997) The Innovator's Dilemma, and Carliss Baldwin and Kim Clark's Design Rules, on the shelves of product engineers during a 2000 visit at one of the Big Three OEMs." Jacobides *et al.* (2016) go on to report a personal communication with Carliss Baldwin where she states: "In the late 1990s, Kim [Clark] as well as Clay [Christensen] were in an evangelizing mode and the frameworks were just out. Kim in particular had a longstanding relationship with the Ford CEO, and I know they discussed our work. At the time, we were more concerned with the risk of power devolving on suppliers (the Intel story) than with the possibility that the framework just didn't fit. This helped shape the views promulgated by the CEO office of Ford."

2 As the certification of parts to comply with regulatory requirements is an important aspect of the integration of the automobile, OEMs' legal and certification capabilities can also be viewed as a subset of their system integration capabilities. However, we describe OEMs' legal and certification capabilities separately because they constitute an important foundation of their architectural advantage (Jacobides *et al.*, 2016).

Technical bottlenecks are key modules of the technology whose performance limits the performance of the system as a whole (Baldwin and Clark, 2000; Baldwin, 2018, 2019) and, thus, represent important technical problems to be solved (Baldwin, 2015). OEMs maintain control over the technical bottlenecks by splitting up the production of the power train and integrating the separately produced parts. Thereby, OEMs turn the power train and system integration into strategic bottlenecks (Baldwin, 2015), which allows them to hierarchically control their suppliers and capture a large share of the economic value. That is, OEMs' legal and certification, power train design, and system integration capabilities are important elements of their architectural advantage, which allows them to control the division of labor and distribution of economic value in the automotive industry manufacturing ICEVs.

However, the technological shift from ICEVs to battery electric vehicles (BEVs) could jeopardize OEMs' architectural advantage. BEVs are propelled by an electric engine instead of an internal combustion engine, which is powered by electric energy stored in batteries instead of fossil fuels stored in fuel tanks. Due to the different types of engines, a different transmission is required for BEVs compared to ICEVs to transmit the rotation of the engine to the rotation of the wheels in order to propel the automobile. Furthermore, BEVs require a different power control of the engine to create the desired driving experience. These changes seem to render the power train of BEVs structurally simpler compared to the power train of ICEVs (Perkins and Murmann, 2018), which could render OEMs' ICEV power train design capabilities irrelevant.[3] The power train represents a core subsystem of automobiles that is tightly integrated with other features to ensure a good driving experience of automobiles (Murmann and Frenken, 2006; Perkins and Murmann, 2018). As a result changes to the structure of the power train may remove some connections between the technical structures in automobiles. This implies that BEVs may be more modular than ICEVs, which could lower the system integration requirements for building automobiles.

Although OEMs' legal and certification capabilities likely remain relevant for BEVs, the OEMs' system integrator role represents "their primary source of control over value creation and capture" in the automotive industry (Jacobides *et al.*, 2016: 1944). Therefore, the technological shift from ICEVs to BEVs challenges important channels of OEMs' control over the architecture of the automotive industry and may prevent OEMs from establishing the same degree of control over the division of labor and distribution of value in the automotive industry manufacturing BEVs. That is, the shift from ICEVs to BEVs may have profound implications for the architecture of the automotive industry, which would affect both OEMs and suppliers.

Hence, the purpose of this study is to examine the question of how the technological shift from ICEVs to BEVs will affect the architecture of the automotive industry. We systematically compare the technological structure of ICEVs and BEVs by creating (i) technical descriptions of the power trains of ICEVs and BEVs to evaluate their structural complexity and (ii) design structure matrices (DSMs) of ICEVs and BEVs at the system level to determine their design parameters and modularity (Schilling, 2000; Murmann and Frenken, 2006).[4] Modularity is the extent to

3 We do not mean to imply that ICEV OEMs have not gained new, largely unrelated technological know-how in battery electric power train technologies by investing for many years in the research and patenting of these technologies. All ICEV OEMS have filed for significant numbers of BEV patents in the past decades as they were looking for alternative power train technologies. But except for Toyota, ICEV OEMs until a few years ago have spent dramatically more money on developing further ICEV technologies than BEV technologies as can be seen in figure 17 of the research by Fredriksson *et al.* (2018). Toyota coincidentally is the largest filer in the world of patents connected to BEV technology, with 22 668 filings in the past 20 years, more than double of Honda, which comes in position 2 (Leggett, 2021). Toyota has had hybrid technology cars on the road since 1997 but has been relatively slow in rolling out pure BEVs. Our key point is that accumulated know-how in ICEV technology is no longer giving ICEV incumbents an advantage over start-ups or companies that did not achieve the same level of technological sophistication in ICEV technology because there is a much more level playing field in pure BEV power trains. In the theoretical language of Tushman and Anderson (1986), pure BEV technology is largely a competency-destroying and not a competency-enhancing new technology because a firm does not need to have mastered ICEV power train technology to master BEV power train technology. An important case in point, Chinese producers could not catch up with foreign OEMs in producing the most advanced ICEV vehicles but in the era of BEVs some new Chinese companies, such as NIO, have reached the technological frontier of BEVs, which alluded them for over three decades. Chinese and not Germans are currently the second-most prolific EV World Intellectual Property Organisation patent filers with a global share of 28%, while the US filing dominates with a 49% share in Quarter 1 of 2020 (Leach, 2021).

4 We focus on the structural complexity of the power train and the modularity of automobiles because this allows us to evaluate potential changes in the level of power train design and system integration capabilities required for building automobiles. Thereby, we can extrapolate how the technological shift from ICEVs to BEVs affects OEMs' control

which the components of a technology can be separated into different modules. Modules reduce the interdependencies among design parameters of the entire system as there will ideally only be interdependencies within a module but not across different modules (Simon, 1962; Baldwin and Clark, 2000). Based on this analysis and the mirroring hypothesis, which suggests that the modularity of a technology determines the structure of the corresponding industry (Baldwin and Clark, 2000), we derive predictions about the future architecture of the automotive industry, focusing on firms involved in the manufacturing of automobiles. Such ex ante predictions may not only permit a strong test of the mirroring hypothesis, but can also serve as strategic guidelines for those industry participants who want to take advantage of technological changes in the industry.

2. Theoretical background

In this section, we will first define what the structure of technologies and the architecture of industries are. Then, drawing on the mirroring hypothesis, we are going to explain why the modularity of a technology determines the architecture of its industry. Lastly, we will describe previous research on the automotive industry that informs our study.

2.1 Defining the structure of a technology and the architecture of an industry

Technologies are tangible or intangible artifacts—"products of human intelligence and effort" (Baldwin and Clark, 2000: 2)—that perform specific functions. Thus, technologies can be described in terms of their structure, the components that constitute the technology, and in terms of their functionality, the purpose for which the technology is constructed (Baldwin and Clark, 2000). Although the structure of a technology can be described in various ways (e.g., Ulrich, 1995; Yoo *et al*., 2010), we characterize the structure of a technology by its design structure and modularity (Baldwin and Clark, 2000): A design structure is constituted by a set of design parameters and the dependencies between them. Design parameters represent the elements of a technology that describe its variable tangible and intangible characteristics. For example, engine type and acceleration are two of the many design parameters of cars. We call design parameter B dependent on design parameter A if a change in design parameter A affects design parameter B in any way. Usually, only a few dependencies between design parameters exist in simple technological structures. In contrast, many dependencies exist in complex technological structures, as several design parameters interact to provide the intended functionality of the technology.

In addition to the design structure of a technology, modularity constitutes an important aspect of the structure of a technology (Baldwin and Clark, 2000; Schilling, 2000; Murmann and Frenken, 2006). We define modularity as the extent to which the components of a technology can be separated into different modules. Modules reduce the interdependencies among design parameters of the entire system as there will ideally be interdependencies only within a module but not across different modules (Baldwin and Clark, 2000; MacCormack *et al*., 2006). Therefore, modules usually have standardized interfaces, which results in two distinct advantages (Langlois, 2002): First, modules can be easily removed and replaced by other modules, which allows for a variety of modules to be integrated in the technology. Second, modules can evolve independently from the rest of the technology, as no coordination with other modules of the technology is necessary. This enables innovation at the subsystem level of the technology. Therefore, modularity is considered as a means to coordinated problem-solving conserving cognitive resources (Colfer and Baldwin, 2016). It is important to note that technologies often differ in their modularity (MacCormack *et al*., 2006).

over the technical bottlenecks of automobiles: the power train and integration of the automobile. Although OEMs' legal and certification capabilities are an important source of OEMs' control over the architecture of the automotive industry, we decided to focus on OEMs' power train design and system integration capabilities as (i) prior research suggests that OEMs' system integrator role represents "their primary source of control over value creation and capture" in the automotive industry (Jacobides *et al*., 2016: 1944), (ii) a detailed technical analysis of automobiles can provide insights into the implications of the technological shift from ICEVs to BEVs for OEMs' power train design and system integration capabilities in the tradition of Baldwin and Clark (2000), and (iii) analyzing how the technological shift affects OEMs' legal and certification capabilities would require nontechnical data that would go beyond the scope of the paper.

The architecture of an industry represents the division of labor—the who does what?—and the distribution of economic value—the who captures what part of the value?—in an industry (Jacobides *et al.*, 2006): Although the architecture of a nascent industry is often in a state of flux, conditions stabilize over time, because industry participants begin to co-specialize, which allows them to make efficient transactions (Williamson, 1975, 1981; Baldwin, 2008). Consequently, a clear division of labor emerges. Irrespective of the division of labor, the firms possessing the capabilities to solve and control the technical bottlenecks of a technology capture the lion's share of economic value in an industry (Baldwin and Clark, 2000; Baldwin, 2015, 2018, 2019). Once a stable industry architecture has emerged, deviating from this architecture is usually costly. That is, the division of labor and the distribution of economic value in an industry usually remain stable over time.

2.2 The mirroring hypothesis: the modularity of a technology determines the architecture of its industry

A central idea of the literature on the relationship between the structure of a technology and the architecture of its industry is the mirroring hypothesis, which suggests that the modularity of a technology determines the architecture of the corresponding industry (Baldwin and Clark, 2000; Pisano and Teece, 2007). The modularity of a technology determines the division of labor in an industry by influencing whether firms can independently specialize in modules of the technology; modular technologies enable firms to independently specialize in modules resulting in efficiency gains (Sturgeon, 2002; Sako, 2004). Although integrated technologies prevent firms from independent specialization because no standardized interfaces exist, they create the opportunity for system integrators to coordinate the knowledge and organize the actors required for the production of the integrated technology (Brusoni and Prencipe, 2001; Brusoni *et al.*, 2001; Tee *et al.*, 2019). Therefore, industries of modular technologies tend to consist of vertically disintegrated firms, each specializing in different modules of the technology (Pisano and Teece, 2007; Argyres and Bigelow, 2010). In contrast, industries of integrated technologies tend to be comprised of vertically integrated firms, each designing and producing all parts of the technology (Pisano and Teece, 2007). Although the vertical (dis)integration of firms is not necessarily tantamount to the division of labor in an industry, as specialized firms can also participate in industries typically consisting of integrated firms and vice versa, the extent of vertical (dis)integration is an important indicator of the division of labor in an industry.

Furthermore, the modularity of the technology determines the distribution of value in an industry by influencing whether the integration of the modules or the specific modules themselves represent the technical bottlenecks of a technology that firms need to control to capture the bulk of economic value. Expanding on this understanding, if a technology is modular, firms possessing the capabilities that enable them to solve and control the technical bottlenecks of a technology usually capture the lion's share of the economic value (Baldwin and Clark, 2000; Pisano and Teece, 2007). In contrast, if a technology is integrated, firms possessing the system integration capabilities usually capture the lion's share of the economic value because the system integration is typically the bottleneck of integrated technologies (Teece, 1986, 2006; Pisano and Teece, 2007; Fixson and Park, 2008).

This theoretical reasoning has generally been supported by previous research (cf. Cabigiosu and Camuffo, 2012; Colfer and Baldwin, 2016). The computer industry is the prime example (Baldwin and Clark, 2000): Initially, system integrators controlled the architecture of the computer industry through their system integration capabilities, which allowed them to capture most of the economic value. However, system integrators lost control of the computer industry when the structure of the computer became modular after IBM introduced the IBM Personal Computer (PC). Henceforth, Microsoft and Intel, as suppliers of the operating system and central processing unit, which represent the bottleneck modules of PCs, captured most of the economic value (Baldwin and Clark, 2000; Pisano and Teece, 2007). That is, the computer industry changed from a vertical to a horizontal architecture, which entailed a migration of value from the system integrators to the suppliers of bottleneck modules (Jacobides and Tae, 2015).

However, the architecture of an industry is also influenced by other factors. For example, previous research suggests that the structure of digital technologies is not necessarily mirrored in the industry architecture, as their coordination can be achieved efficiently without mirroring (Colfer and Baldwin, 2016). Furthermore, firms may engage in strategic mirror-breaking to gain an advantage in industries built around complex technologies with short innovation cycles resulting in industry architectures that differ from the structure of their corresponding technologies (Colfer and Baldwin, 2016; Windrum *et al.*, 2019). Most notably, research showed that the regulatory requirements imposed on an industry influence the industry architecture; unlike system integrators in the PC industry, automobile OEMs have to fulfill much more stringent legal requirements to assure the safety of technology, which has contributed to their control over the architecture of the automotive industry (Jacobides *et al.*, 2016). Taken together, research suggests that even though various factors influence the architecture of an industry, the modularity of a technology is an important determinant of the architecture of an industry (Baldwin and Clark, 2000; Colfer and Baldwin, 2016).

2.3 The structure of automobiles and the architecture of the automotive industry

As noted, OEMs control the architecture of the automotive industry manufacturing ICEVs because they possess an architectural advantage, which is rooted in their legal and certification, power train design, and system integration capabilities. As these capabilities enable OEMs to solve and control the technical bottlenecks of ICEVs, OEMs can hierarchically control their suppliers through proprietary designs that prevent standardized interfaces, requirements to make specific investments in machinery to produce the parts, and competitive bidding for high-volume contracts (Jacobides *et al.*, 2016).[5] Furthermore, this allows OEMs to capture the lion's share of the value even though they outsource the production of most parts to suppliers. That is, OEMs determine the division of labor and distribution of value in the industry manufacturing ICEVs.

However, the technological shift from ICEVs to BEVs could jeopardize OEMs' architectural advantage. BEVs are propelled by an electric engine instead of an internal combustion engine, which is powered by electric energy stored in batteries instead of fossil fuels stored in fuel tanks. Due to the different types of engines, a different transmission is required for BEVs compared to ICEVs to transmit the rotation of the engine to the rotation of the wheels in order to propel the automobile. Furthermore, BEVs require a different power control of the engine to create the desired driving experience. Overall, these changes seem to render the power train of BEVs structurally simpler compared to the power train of ICEVs (Perkins and Murmann, 2018). Some knowledge related to the power train of ICEVs (and hybrids) may remain relevant to the power train of BEVs, such as knowledge about the physics of propelling an automobile under various operating conditions, which may help OEMs to develop power train design capabilities related to BEVs (Cohen and Levinthal, 1990). But most of the OEMs' knowledge related to the design of the engine and transmission of ICEVs is nevertheless rendered irrelevant.

As the power train represents a core subsystem of automobiles that is tightly integrated with other features to create the driving experience of automobiles (Murmann and Frenken, 2006; Perkins and Murmann, 2018), changes to the structure of the power train may change their links to other technical structures in automobiles and aspects of their driving experience. For example, changes to the engine, transmission, and differential may change their relationship to the range, acceleration, speed, and drive dynamics of automobiles. Therefore, changes to the power train of automobiles may also alter the modularity of automobiles. As a simpler power train may remove some links between the design parameters in automobiles, BEVs may be more modular than ICEVs, which would render OEMs' subsystem integration capabilities related to the power train of ICEVs much less useful, lowering the overall system integration requirements of automobiles.[6]

5 Although OEMs possess considerable power over their suppliers, their approach to managing suppliers seems to be changing. Due to programmable automation, suppliers now appear to require fewer specific investments in machinery to produce the parts. Furthermore, OEMs now seem to seek longer-term relationships with suppliers. Nevertheless, OEMs still tightly control their suppliers and the architecture of the automotive industry.

6 It is important to note that even though the integration of the power train into the automobile represents an important aspect of OEMs' system integration capabilities, it represents only a subset of the system integration capabilities required for building automobiles. Therefore, changes in the power train of the automobile only partly affect OEMs' system integration capabilities.

The structurally simpler power train of BEVs may also have implications for OEMs' legal and certification capabilities. As the power train of BEVs seems to consist of entirely different technological components compared to the power train of ICEVs, OEMs' legal and certification capabilities related to the power train of ICEVs may become obsolete. For example, different legal and certification capabilities may be required to certify the parts of an ICEV engine compared to a BEV engine. Although OEMs' legal and certification capabilities may remain relevant for parts unrelated to the power train of BEVs, OEMs likely need to acquire the relevant legal and certification capabilities for BEV power trains. Therefore, OEMs' legal and certification capabilities related to the power train of ICEVs may become largely irrelevant, rendering OEMs' legal and certification capabilities overall partly irrelevant.

Taken together, the technological shift from ICEVs to BEVs may render OEMs' ICEV power train design capabilities largely irrelevant, requiring them to learn new BEV power train skills, lowering the overall system integration requirements for building automobiles, and rendering OEMs' legal and certification capabilities partly irrelevant. This suggests that the technological shift from ICEVs to BEVs could potentially be a competency-destroying innovation for OEMs (Tushman and Anderson, 1986). Therefore, the technological shift from ICEVs to BEVs challenges important channels of control of OEMs over the architecture of the automotive industry and may prevent OEMs from establishing the same degree of control over the division of labor and distribution of value in the automotive industry manufacturing BEVs. Despite the partly continued relevance of OEMs' legal and certification capabilities, which has cemented their control over the architecture of the automotive industry in the past, the potentially lower overall system integration requirements for BEVs may be problematic as OEMs' system integrator role represents "their primary source of control over value creation and capture" in the automotive industry (Jacobides *et al.*, 2016: 1944). That is, the shift from ICEVs to BEVs may have profound implications for the architecture of the automotive industry, which would affect both OEMs and suppliers.

While the technological shift from ICEVs to BEVs may have predominantly negative implications for OEMs, this may be a double-edged sword for incumbent suppliers. On the one hand, a structurally simpler power train could render suppliers' capabilities related to the manufacturing of parts for ICEV power trains partly irrelevant and reduce their share of value. For example, suppliers' knowledge related to ICEV power train parts like cylinder heads or piston rods likely becomes irrelevant, with their knowledge having limited usefulness for BEV power trains. On the other hand, modular BEVs may permit suppliers who possess capabilities allowing them to solve and control the technical bottlenecks of BEVs to capture a larger share of the value. For example, suppliers' knowledge related to BEV power train parts like battery cells likely becomes central to automobiles. Therefore, the technological shift from ICEVs to BEVs may represent both a threat and an opportunity for suppliers. Taken together, the technological shift from ICEVs to BEVs may reshape the architecture of the automotive industry.

In light of these developments, the question arises as to how the technological shift from ICEVs to BEVs will change the architecture of the automotive industry. We break this general question down into three specific research questions that we attempt to answer in this study: First, what are the differences in the design structure of ICEVs and BEVs? Second, what are the differences in the modularity of ICEVs and BEVs? Third, what are the implications of the differences in the design structure and modularity of ICEVs and BEVs for the future architecture of the automotive industry?

3. Methods

To answer our research questions, we compare the design structure and modularity of ICEVs and BEVs at the system level using DSMs (Steward, 1981; Eppinger *et al.*, 1994). DSMs are ideal for this comparison because they depict not only the design parameters but also the dependencies between these design parameters, which can be used to compute the modularity of a technology (Baldwin and Clark, 2000; Eppinger and Browning, 2012). This allows us to not only determine the differences in the design structure and modularity of both technologies but also to make predictions about the future architecture of the automotive industry based on the mirroring hypothesis. Furthermore, system-level DSMs allow us to examine whether the shift from ICEVs to BEVs affects the system integration requirements of automobiles. This enables us to draw conclusions on the relevance of OEMs' system integration capabilities. Furthermore, we create technical descriptions of the power trains of ICEVs and BEVs to evaluate their structural complexity. Thereby, we also provide an overview of the technical and value differences between ICEVs and BEVs at the power train level to illustrate how the shift from ICEVs to BEVs affects the structure and value of power trains. Overall, we can thereby determine whether the reasoning of Jacobides *et al.* (2006, 2016) that the OEMs dominate the architecture of the automotive industry manufacturing ICEVs because they possess an architectural advantage is generalizable to the architecture of the automotive industry manufacturing BEVs. In the following, we are going to explain what DSMs are and what our rationale regarding the use of DSMs is before we detail our approach to data collection and analysis.

3.1 Design structure matrices

DSMs depict the design structures of technologies by representing the design parameters and dependencies between them (Baldwin and Clark, 2000; Eppinger and Browning, 2012). In DSMs, the structure of automobiles can be represented at two levels: First, DSMs can depict the design parameters at the level of the major structures and functionalities of automobiles, such as the engine type and acceleration. Second, DSMs can depict the design parameters representing all structures and functionalities of automobiles. This level of analysis not only displays the major structures of the technology but also describes elementary components, such as screws and washers.

We use DSMs to depict the design parameters at the level of the major structures and functionalities of automobiles because these components determine the modularity of ICEVs and BEVs. In contrast, the elementary components are by nature highly dependent. Consequently, an analysis of the elementary components would provide little insight into our research questions (c.f. MacCormack *et al.*, 2006). Furthermore, the design parameters representing the major structures and functionalities of automobiles are used in practice to develop new automobile architectures. Therefore, the appropriate level of analysis for our research questions and context is that of the major structures and functionalities of automobiles.

The dependencies between design parameters are the second element that constitutes the design structure of a technology; this is represented in DSMs (Baldwin and Clark, 2000; MacCormack *et al.*, 2006; Eppinger and Browning, 2012). We call design parameter B dependent on design parameter A if a change in design parameter A affects design parameter B in any way. Dependencies always imply directions: if B depends on A, A influences B. However, this does not necessarily mean that A also depends on B, and thus, B influences A. Such bidirectional dependencies would be referred to as symmetric dependencies, whereas unidirectional dependencies are referred to as asymmetric dependencies. Furthermore, it is important to differentiate between direct and indirect dependencies. If B directly depends on A, A influences B directly. However, even if B may not directly depend on A, B may indirectly depend on A via a third design parameter C; if B depends on C and C depends on A, A influences B indirectly via C. Although DSMs contain information about the direct and indirect dependencies within a system, only the direct dependencies are evident in DSMs.

Both direct and indirect dependencies are important to measure the modularity of a technology (MacCormack *et al.*, 2006). By definition, the modularity of a technology is low if many direct and indirect dependencies between the design parameters of the technology exist. If design parameters are changed in any way and other design parameters depend directly or indirectly on these design parameters, the dependent design parameters are directly and indirectly affected by this change. In other words, changing design parameters incurs cost in the sense that other dependent design parameters also need to be adjusted.

The metric of propagation cost can be used to measure the cost of adjusting a design parameter. Propagation cost measures the average proportion of design parameters that are affected when a random design parameter of a technology is changed (MacCormack *et al.*, 2006, 2012; Baldwin *et al.*, 2014). Consequently, high propagation cost indicates low modularity of a technology, whereas low propagation cost indicates high modularity of a technology. Propagation cost can be computed based on the information represented in DSMs and is a standard measure for modularity, which has been used by earlier research (e.g., MacCormack *et al.*, 2006, 2012). Thus, propagation cost represents an adequate measure for the modularity of a technology and can be used to measure the modularity of automobiles. We describe the calculation of propagation cost in detail in the data analysis section.

3.2 Data collection

The data collection was challenging because of the perceived sensitivity of data that we requested from global automotive companies and start-ups to construct the DSMs of ICEVs and BEVs. This perception exists because the data can provide insights into the design structure of automobiles. The worry we encountered was that if an automotive company or start-up discloses this design structure, competitors could use these data to draw inferences on the company's design structure decisions and strategy.

We reached out to four global automobile companies that produce both ICEVs and BEVs, and six start-ups exclusively producing BEVs. Two auto firms and five start-ups did not respond to our request for data or declined to collaborate.[7] However, two global automobile companies and one start-up agreed to collaborate with us on the condition that we would not disclose the identity of the firms. One global automobile company is headquartered in Europe, whereas the other is headquartered in Asia. The start-up is located in Europe and has no history of producing ICEVs or electric hybrid vehicles.

We contacted both global automotive companies and start-ups because they likely differ fundamentally in how they design vehicles. Engineers from global automobile companies may approach the design of BEVs similarly to the design of ICEVs, as their mental models of vehicles are likely rooted in their previous experience with ICEVs. In contrast, engineers from start-ups may approach the design of BEVs differently than the design of ICEVs as they do not possess pre-existing mental models. As engineers from global automobile companies have designed highly integrated ICEVs, they may also design highly integrated BEVs, whereas engineers from start-ups may design more modular BEVs. That is, engineers from global automobile companies and engineers from start-ups might fundamentally differ in their mental models, which may materialize in differences in the modularity of BEVs.[8]

One engineer from each global automobile company and one engineer from the start-up collaborated with us to construct and fill in the DSMs. The engineers from the global automobile companies are experts in ICEVs and BEVs. One of these engineers is the senior manager in the department that is responsible for integrating all technical systems of both ICEV and BEV platforms The other engineer is involved in the supply chain management of ICEVs and BEVs. The effective management of the supply chain of ICEVs and BEVs requires detailed knowledge of the design parameters and the dependencies between them. The engineer of the BEV start-up is the most senior technical officer in the company and is directly involved in the design of the entire BEV. Thus, all engineers are suitable informants for our study.

Although this sample is neither random nor fully representative, it is a purposive sample that allows us to *explore* the design structure and modularity of ICEVs and BEVs. We follow previous research on modularity whose purpose was to make predictions about the future architecture of an industry and not propose new theories or formally test hypotheses (e.g., MacCormack *et al.*, 2006). Furthermore, the population from which the firms are drawn is small compared to other industries, due to the economies of scale required in the automotive industry. In 2020, 10 firms controlled approximately 50% of the global car market.[9] Thus, having obtained data from three firms in the automotive industry, which has been challenging due to the sensitivity of the requested data, should be regarded as an important first step in allowing us to offer evidence-based conclusions that future research can build on. What is more, the size of the sample needs to be evaluated in terms of whether the data are used to confirm the researcher's conjectures or

7 One automobile company first agreed to collaborate but later did not allow its engineers to fill in the Excel file and share it with us because they perceived the information to be strategically sensitive.

8 We thank the reviewers for raising this important point.

9 *Source*: https://www.statista.com/statistics/316786/global-market-share-of-the-leading-automakers/ (accessed February 26, 2022).

to disconfirm them. As Popper (1959) highlighted, one observation is sufficient to disconfirm a regularity, but even a large sample can never fully prove a regularity. Since all three informants in this study disconfirm our original conjecture, our data are far more powerful than they may appear on first glance.

We constructed the DSMs in three steps: First, we created an overview of the common functions as well as the corresponding first-order and second-order structures of ICEVs and BEVs at the power train level by conducting four unstructured interviews with the design engineer from one incumbent OEM. Furthermore, we conducted an unstructured interview with the supply chain engineer to create an overview of the value pertaining to each module of the power train. These unstructured interviews lasted 12 h in total and allowed us to develop an intimate understanding of the technical and value differences between ICEVs and BEVs at the power train level. Second, we conducted three more unstructured interviews, which lasted 5 h in total, with the design engineer from the incumbent OEM to arrive at a set of design parameters of ICEVs and BEVs at the system level. Based on these design parameters, which are used in practice to develop new automobiles, we then created an Excel file that would enable our informants to determine the dependencies between these design parameters. Third, we asked each engineer to fill in the dependencies between the design parameters in the DSMs. Instead of simply indicating whether a dependency exists or not by using 1 and 0, we asked our informants to indicate the strength of the dependency between the design parameters. Although the state-of-the-art method regarding the calculation of propagation cost currently does not allow us to take the strength of direct and indirect dependencies into account, the average strength of direct dependencies is nevertheless informative regarding the general strength of the direct dependencies within a system. To facilitate this process, we sent our informants a document with instructions on how to fill in the DSMs (see Supplementary Appendix A). Filling in one of these DSMs took each of our informants on average 5 h. The informants were not able to see the DSMs of the other informants to ensure the independence of their responses.[10]

It is important to note that these data could be somewhat subjective as they depend on the mental models of our informants. Due to differences in their expertise and organizational membership, our informants may interpret the design parameters and evaluate the dependencies between them somewhat differently. Therefore, variability in the responses of our informants might not indicate true differences in the structure and modularity of automobiles but simply a different understanding of the design parameters and dependencies between them.

In this light, we took several measures to ensure the validity of our data. First, we asked our informants to indicate whether the technological structure of the power trains and the corresponding DSMs made sense to them. All informants indicated that this was the case. Second, we designed the instructions for filling in the DSMs to facilitate the interpretation of the design parameters by providing examples of the design parameters (see Supplementary Appendix A). For instance, for the design parameter driving efficiency, we wrote 5 l (6 kWh) on 100 km vs. 12 l (20kWh) on 100 km. Third, to ensure that the variability in the responses of our informants would represent true differences in the structure and modularity of automobiles and not simply different understandings of the design parameters and dependencies between them, we triangulated the data in one of the global automobile companies where we were able to recruit a second informant.[11] This informant is an engineer who is part of the team that is responsible for integrating all technical systems of both ICEV and BEV platforms and is therefore a suitable informant. The informant indicated that the technological structure of the power trains and the corresponding DSMs made sense. Furthermore, the informant only adjusted one of the 784 cells of the ICEV DSM and seven of the 784 cells of the BEV DSM, which suggests that the dependencies between the design parameters were understood and evaluated consistently. We averaged the DSMs of the informants from the same global automobile company to approximate the true DSMs of the ICEV and BEV for the corresponding company. We used the average ICEV and BEV DSM of this company in the data analysis.

10 The two engineers from the incumbent OEMs spent, on average, a combined 10-h filling out one ICEV and one BEV DSM.

11 It was not possible to recruit multiple informants for the other two companies.

3.3 Data analysis

Based on the overview of the common functions as well as the corresponding first-order and second-order structures of ICEVs and BEVs at the power train level, we analyzed the technical differences between both technologies to better understand the technological shift from ICEVs to BEVs. We then analyzed the DSMs to examine the modularity of ICEVs and BEVs at the system level. To analyze the DSMs, we first averaged the two ICEV DSMs and the three BEV DSMs we received from the three companies to approximate the design structures of ICEVs and BEVs, which represent the cases by which we seek to support or refute our conjecture that BEVs are more modular than ICEVs. Second, we computed the visibility matrices for each technology (MacCormack *et al.*, 2006): The visibility matrix V_t of each technology $t\,(t \in \{\mathrm{ICEV}, \mathrm{BEV}\})$ can be formally defined as follows:

$$V_t = I(P_t) + \sum\nolimits_{i=1}^{P_t} M_t^i \text{ with all positive values in } V_t \text{ set equal to } 1,$$

where $I(P_t)$ is the identity matrix of order P_t, where P_t refers to the number of design parameters in the first-order matrix M_t of technology t; the first-order matrix M_t is the DSM of technology t containing the *direct* dependencies between the design parameters that are represented with a value of 1 in the corresponding cell. We included the identity matrix in the computation of the visibility matrices V_t because this allows us to consider that changing a design parameter always affects the design parameter itself. While the direct dependencies between the design parameters of a technology are represented by the first-order matrix M_t, raising the first-order matrix M_t to successive powers until P_t computes all indirect dependencies between the design parameters. Consequently, the visibility matrix V_t contains the direct and indirect dependencies between the design parameters of a technology.

Based on the visibility matrix V_t, we calculated the propagation cost of each technology t (MacCormack *et al.*, 2006; Baldwin *et al.*, 2014): The propagation cost of a technology t can be formally defined as follows:

$$\text{Propagation Cost}_t = \frac{\sum_{p=1}^{P} \mathrm{VFI}_{pt}}{P_t^2} = \frac{\sum_{p=1}^{P} \mathrm{VFO}_{pt}}{P_t^2},$$

where $p = 1, \ldots, P_t$ refers to the design parameters in the DSM of technology t, VFI_{pt} refers to the Visibility-Fan-In of parameter p of technology t, and VFO_{pt} refers to the Visibility-Fan-Out of parameter p of technology t. VFI_{pt} and VFO_{pt} are metrics at the parameter level that are calculated based upon the visibility matrix V_t. VFI_{pt} measures the number of parameters that directly or indirectly depend on parameter p of technology t relative to the total number of parameters of technology t. VFI_{pt} is calculated by adding the numbers in the pth column and dividing by the number of rows of the visibility matrix V_t. VFO_{pt} measures the number of parameters parameter p of technology t directly or indirectly depends on. VFO_{pt} is calculated by adding the numbers in the pth row and dividing by the number of columns of the visibility matrix V_t. The propagation cost is a metric at the system level that can be calculated based upon VFI_{pt} or VFO_{pt}. $\sum_{p=1}^{P} \mathrm{VFI}_{pt}$ and $\sum_{p=1}^{P} \mathrm{VFO}_{pt}$ count the total number of direct and indirect dependencies in the visibility matrix by columns or rows. As the total number of direct and indirect dependencies does not change and the number of columns and rows by which this number is divided always is the same due to the symmetry of DSMs, $\sum_{p=1}^{P} \mathrm{VFI}_{pt}$ and $\sum_{p=1}^{P} \mathrm{VFO}_{pt}$ yield the same value and, ultimately, the same propagation cost. However, we computed the propagation cost based on VFI_{pt} and VFO_{pt} to check our calculations. High values of propagation cost indicate high system complexity, which implies low modularity, whereas low values of propagation cost indicate low system complexity, which implies high modularity. Supplementary Appendix B provides further explanations regarding the interpretation and meaning of visibility matrices and DSMs.

4. Findings

In the following, we are first going to describe the technical and value differences between ICEVs and BEVs at the power train level before we provide data on the modularity of both technologies at the system level.

4.1 Technical and value differences between ICEVs and BEVs at the power train level

Figures 1 and 2 provide an overview of the common functions as well as the corresponding first-order and second-order structures of ICEVs and BEVs at the power train level.

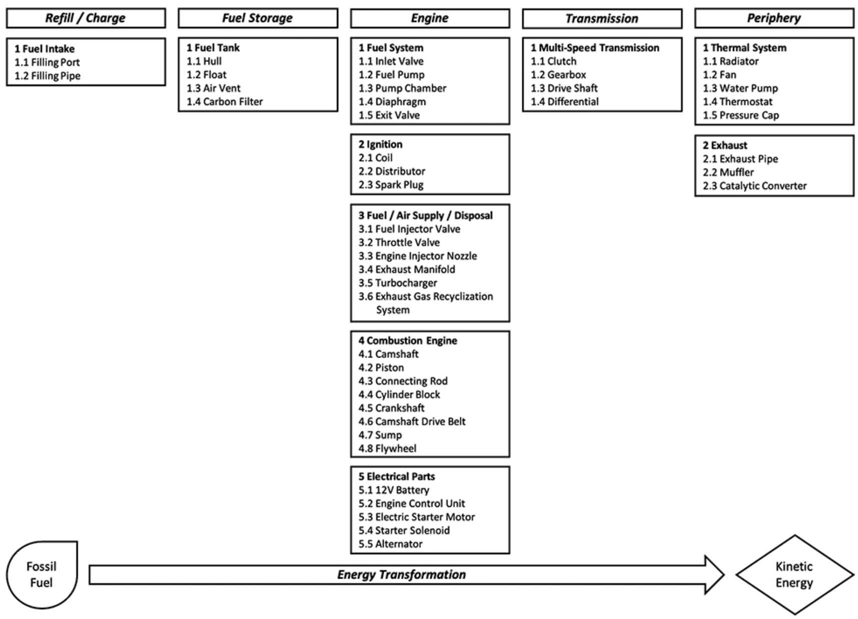

Figure 1. The first-order and second-order structures of the power train of an ICEV that transforms energy in the form of fossil fuel into kinetic energy (movement of the automobile). The structures of the power train of ICEVs are organized by the common functions of the power trains of ICEVs and BEVs, which are represented by the boxes with bold and italicized letters. The first-order structures are named at the top of each box in bold. The corresponding second-order structures are enumerated below the first-order structures in the same boxes

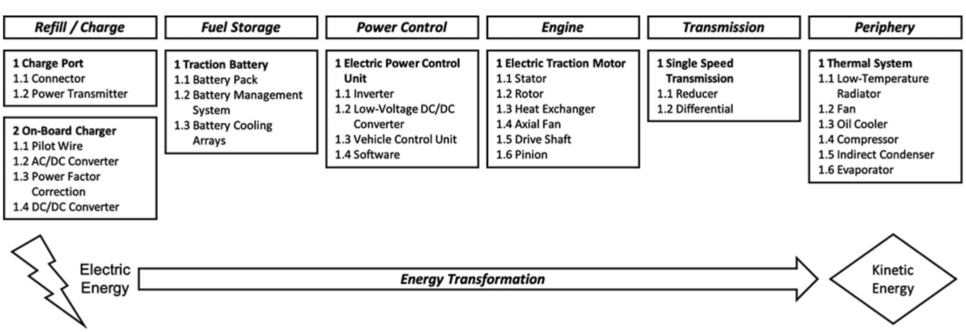

Figure 2. The first-order and second-order structures of the power train of a BEV that transforms energy in the form of electric energy into kinetic energy (movement of the automobile). The structures of the power train of BEVs are organized by the common functions of the power trains of ICEVs and BEVs, which are represented by the boxes with bold and italicized letters. The first-order structures are named at the top of each box in bold. The corresponding second-order structures are enumerated below the first-order structures in the same boxes

Although the first-order and second-order structures of ICEVs and BEVs at the power train level fulfill almost identical functions, the corresponding first-order and second-order structures of the two technologies are fundamentally different. It is striking that the power train of ICEVs consists of 10 first-order and 45 second-order structures, whereas the power train of BEVs consists of only 7 first-order and 27 second-order structures. That is, BEVs have 30% fewer first-order and 40% fewer second-order structures compared to ICEVs. These differences mainly result from the engine of the power trains: While the engine in an ICEV power train consists of 6 first-order and 27 second-order structures, the engine in a BEV power train consists of 1 first-order and 6 second-order structures. This supports the notion that the power train of BEVs is structurally simpler compared to ICEVs because the engine of BEVs consists of fewer first-order and second-order structures than the engine of ICEVs. Furthermore, the first-order and second-order structures of BEVs are technologically almost completely different from ICEVs. These structural differences between the power trains of ICEVs and BEVs result from the different types of energy (fossil fuel vs. electric energy) that both technologies transform into kinetic energy (movement of the automobile). Overall, this suggests that the technological shift from ICEVs to BEVs renders OEMs' power train design capabilities largely irrelevant.

Table 1 provides an overview of the approximate value of each power train module of ICEVs and BEVs. For the sake of simplicity, we compare the approximate value of diesel ICEV power trains to the approximate value of BEV power trains.

Although the power trains of (diesel) ICEVs and BEVs have approximately the same value ($5930 for a diesel ICEV vs. $6020 for a BEV), there are considerable value differences between the modules fulfilling the common functions of ICEVs and BEVs. While the modules allowing the refill of an ICEV cost about $10, the modules allowing the charge of a BEV cost about $420. It is striking that the modules for fuel storage differ considerably in their value: The fuel tank of an ICEV is $20, whereas the traction battery for a BEV is $3300. Furthermore, it is notable that the modules for the engine of ICEVs add up to $4100, whereas the modules for the engine and power control of BEVs add up to only $1400. Moreover, the transmission module of ICEVs, which is $1100, is worth more than the transmission module of BEVs, which is $700. Similarly,

Table 1. Overview of the approximate value of each power train module of ICEVs and BEVs

ICEV		BEV	
Module	Value in $	Module	Value in $
Refill/charge			
Fuel intake	10	Charge port	20
		On-board charger	400
Fuel storage			
Fuel tank	20	Traction battery	3300
Power control			
		Electric power control unit	200
Engine			
Fuel system	400	Electric traction motor	1200
Ignition	200		
Fuel/air supply/disposal	800		
Combustion engine	2200		
Electric parts	500		
Transmission			
Multi-speed transmission	1100	Single-speed transmission	700
Periphery			
Thermal system	200	Thermal system	200
Exhaust	500		
Total value	5930	Total value	6020

Notes: (1) Value in $ indicates the approximate value in $. (2) ICEV value in $ based on a diesel ICEV power train. (3) The value of a gasoline ICEV power train is approximately $3100. Gasoline power trains are 50% cheaper because diesel engines require higher-grade parts to withstand the higher heat levels, additional technologies to control emissions, and the fact that simply fewer diesel engines are built. Diesel engines also last longer, partly justifying their higher costs. The higher costs of diesel power trains lie in the engine and the periphery (exhaust) system.

Table 2. Overview of the design parameters of ICEVs and BEVs at the system level

Index	Design parameter
A	Range
B	Acceleration
C	Speed
D	Driving efficiency
E	Fueling/charging time
F	Fueling/charging type
G	Exterior proportions
H	Car type
I	Fuel tank capacity/battery capacity
J	Engine type
K	Engine position
L	Differential
M	Thermal operating conditions
N	Crash safety level
O	Cabin seating position
P	Capacity of trunk/frunk
Q	Transmission hump/Cardan shaft
R	Noise level inside
S	Noise level outside
T	48 V board energy supply
U	Vehicle sensor system
V	Chip processing power
W	ECU software
X	Interior proportions
Y	Steering angle
Z	Green house concept
AA	Drive dynamics
AB	Battery type

Notes: These design parameters are considered when engineers design an entirely new car. The design parameters of ICEVs and BEVs can be regarded as identical. Even though ICEVs and BEVs differ structurally from each other at the power train level, which causes some differences in the design parameters at the system level, the corresponding design parameters are functionally equivalent. Consequently, we treat fueling/charging time, fueling/charging type, and fuel tank capacity/battery capacity as identical. All informants agreed that these design parameters need to be considered when engineers design an entirely new car.

the modules constituting the periphery of ICEVs are worth $700, whereas the module constituting the periphery of BEVs is worth $200. That is, even though the power trains of (diesel) ICEVs and BEVs have about the same value, the value distribution differs considerably between both power trains, as the most valuable modules do not pertain to the engine anymore but to the fuel storage. This is true for both diesel and gasoline ICEVs.

4.2. Modularity of ICEVs and BEVs at the system level

Table 2 provides an overview of the design parameters of ICEVs and BEVs at the system level.

Although the first-order and second-order structures of ICEVs and BEVs differ significantly at the power train level, the design parameters of both technologies can be regarded as identical at the system level. That is, the same 28 design parameters need to be considered when ICEVs or BEVs are developed, as agreed by all informants. This shows that while ICEVs and BEVs structurally differ at the power train level, both technologies are structurally similar at the system level.

Figure 3 depicts the average ICEV and BEV DSMs at the system level. Table 3 shows a comparison of the quantitative data of ICEVs and BEVs at the system level based on the ICEV and BEV DSMs. We compare the findings from automobile companies and the BEV start-up in detail in Supplementary Appendix C to explore potential differences in the modularity of automobiles between incumbents and start-ups.

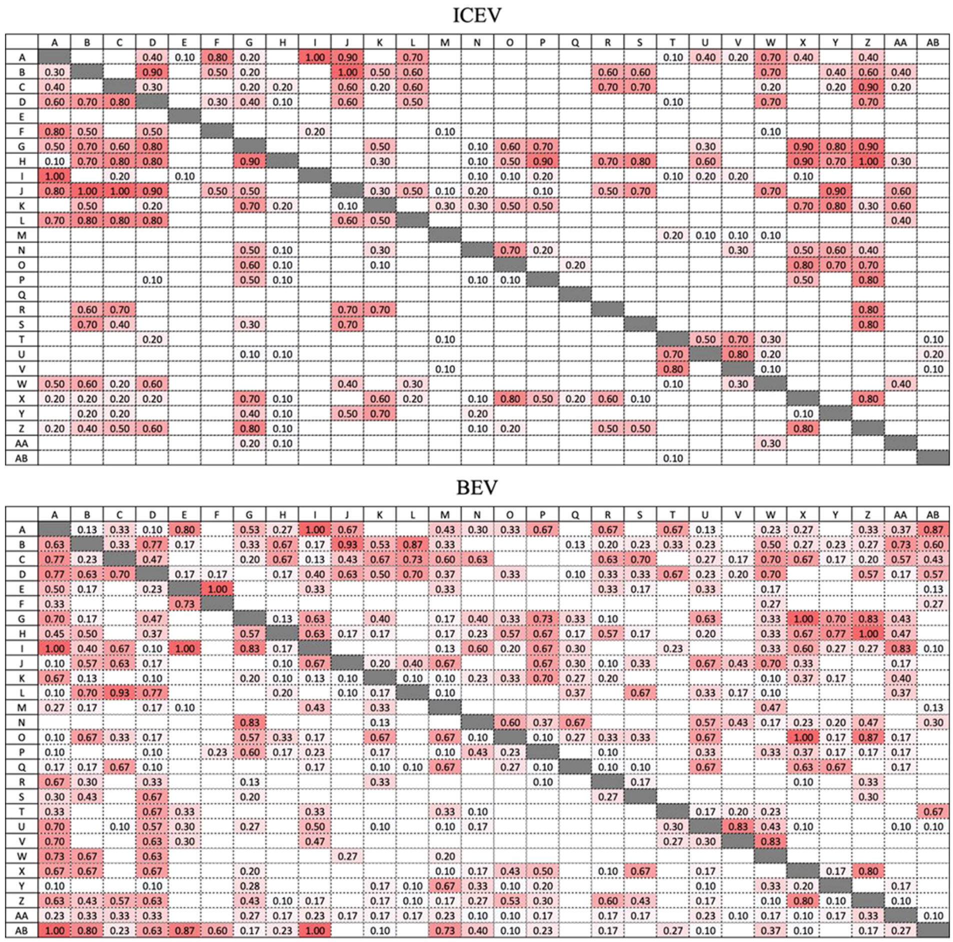

Figure 3. The averaged DSMs of ICEVs (top) and BEVs (bottom) of all firms at the system level. The numbers (0.10–1.00) in the cells indicate the strength of the dependencies between the design parameters at the system level. For better illustration, the strength of the dependencies is visualized with shades of gray. The weaker the dependency, the lighter the gray. Blank cells indicate no dependency. The index letters in the first row and column refer to the design parameters as listed in Table 2

Table 3. Comparison of quantitative data of ICEVs and BEVs at the system level based on the corresponding DSMs

	ICEVs	BEVs
Design parameters	28	28
Direct dependencies (% of total 784 cells)	230 (29.34%)	421 (53.70%)
Average direct dependency relative to total 784 cells	0.129	0.162
Average direct dependency (relative to direct dependencies)	0.439 (230)	0.301 (421)
Symmetric dependencies	166	294
Propagation cost	0.931	1.000

Notes: We conducted robustness checks of these results with the individual DSMs of each firm. The robustness check of company A supported the conclusion, as the propagation cost of the BEV was higher (0.966) than the propagation cost of the ICEV (0.898). Although the robustness check of company B indicated that both ICEV and BEV have the same propagation cost (0.898), this does not change the conclusions meaningfully as this still suggests that both ICEVs and BEVs are highly integrated technologies. The robustness check of the start-up C also corroborated the conclusion that BEVs are highly integrated technologies as the propagation cost of BEVs was similar to the propagation cost of the global automobile companies' BEVs (0.966). This strongly corroborates our conclusion that, irrespective of the different mental models of our informants, both ICEVs and BEVs are highly integrated technologies.

Table 4. Inter-rater reliabilities for the ICEV and BEV DSMs by firm measured by the ICC(1)

	A	B	C
A	1	0.878 [0.861; 0.893]	
B	0.810 [0.784; 0.832]	1	
C	0.352 [0.289; 0.412]	0.397 [0.337; 0.454]	1

Note: The upper triangular matrix depicts the ICC(1) of the ICEV DSMs; the lower triangular matrix depicts the ICC(1) of the BEV DSMs; 95% CIs are in square brackets; and all $P < 0.001$.

The DSMs suggest that BEVs appear to contain a higher number of dependencies than ICEVs. Indeed, the number of direct dependencies is 230 for the ICEVs and 421 for the BEVs, which means that 29.34% of all 784 cells of ICEVs and 53.70% of all 784 cells of BEVs contain a direct dependency. The average direct dependency relative to all 784 cells is similar for BEVs (0.162) compared to ICEVs (0.129), and the average direct dependency relative to all direct dependencies of the technology is lower in BEVs (0.301) compared to ICEVs (0.439). Furthermore, BEVs have more symmetric dependencies (294) than ICEVs (166).

Overall, the data suggest that BEVs seem to have more, albeit weaker, direct dependencies than ICEVs. The propagation cost, which considers both direct and indirect dependencies, is slightly higher for the BEVs (1.000) compared to the ICEVs (0.931) of the global automobile companies. That is, the data suggest that contrary to what we expected, BEVs are slightly less modular than ICEVs. That is, both ICEVs and BEVs seem to be highly integrated technologies. This conclusion is confirmed in robustness checks, in which we computed the propagation cost of ICEVs and BEVs separately for each firm. Thus, system integration capabilities appear to be as relevant for BEVs as they are for ICEVs.

As described above, the mental models of engineers at OEMs and start-ups might be different, which should result in DSMs varying in dependencies and the strength of these dependencies. Table 4 shows the inter-rater reliabilities for the ICEV and BEV DSMs by informant measured by the intraclass correlation coefficient 1 (ICC(1)), which computes the consistency between the responses of the informants based on a one-way ANOVA (Bartko, 1966; Shrout and Fleiss, 1979; McGraw and Wong, 1996). While the inter-rater reliabilities of informants of companies A and B are excellent for both the ICEV (ICC(1) = 0.878, 95% confidence interval [CI] = [0.861, 0.893], $P < 0.001$) and BEV (ICC(1) = 0.810, 95% CI = [0.784, 0.832], $P < 0.001$), the inter-rater reliabilities of informants of companies A and C (ICC(1) = 0.352, 95% CI = [0.289, 0.412], $P < 0.001$) and informants of companies B and C (ICC(1) = 0.397, 95% CI = [0.337, 0.454], $P < 0.001$) are only fair to poor for the BEV. This suggests that while engineers of the global automobile companies A and B and the engineer of the start-up company C saw BEVs as similarly integrated, they differed in their perception of what specific design parameters of BEVs had the greatest dependencies. Irrespective of the apparent differences in the mental models of the engineers, we consistently find that both ICEVs and BEVs are highly integrated technologies.

Overall, our findings suggest that both ICEVs and BEVs are highly integrated technologies, with BEVs being slightly less modular than ICEVs. To explain this surprising finding, we constructed a difference matrix by subtracting the first-order visibility matrix of ICEVs from the first-order visibility matrix of BEVs (see Figure 4).

The difference matrix shows that BEVs generally introduce more direct dependencies than they remove. It is especially striking that the range (A), acceleration (B), driving efficiency (D), battery capacity (I), thermal operating conditions (M), ECU software (W), and battery type (AB) seem to be much more integrated with other design parameters in BEVs than in ICEVs. One explanation for this is that storing electric energy in batteries and using it to move the automobile efficiently through space under various operating conditions seem to require a much more intricate interplay of the design parameters of automobiles. Furthermore, the transmission hump/Cardan shaft (Q), noise level inside (R), noise level outside (S), vehicle sensor system (U), interior proportions (X), and drive dynamics (AA) are much more integrated with the other design parameters in BEVs compared to ICEVs. These additional dependencies may be partly explained by the position of

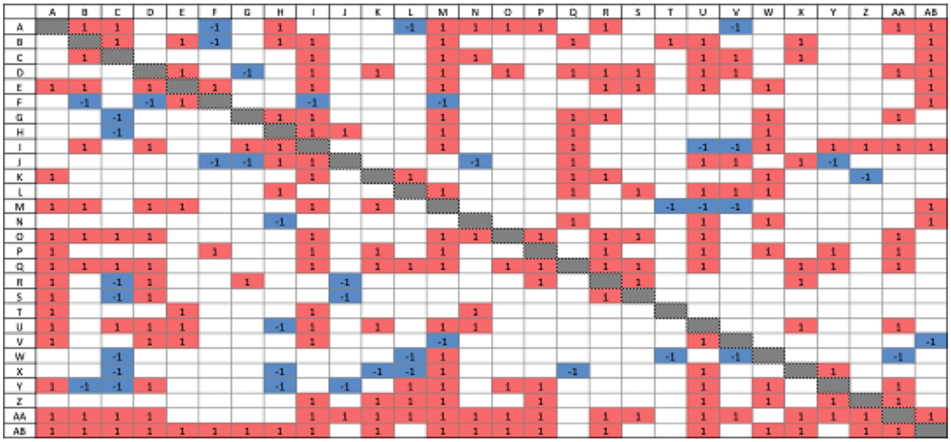

Figure 4. The difference matrix of BEVs and ICEVs. Cells containing the number 1 indicate that BEVs contain a direct dependency between the corresponding design parameters that does not exist in ICEVs. Cells containing the number −1 indicate that BEVs do not contain a direct dependency between the corresponding design parameters that does exist in ICEVs. Empty cells indicate that either a direct dependency between the corresponding design parameters in both ICEVs and BEVs exists or that no direct dependency between the corresponding design parameters exists in either ICEVs or BEVs. The index letters in the first row and column refer to the design parameters as listed in Table 2

the electric engine in BEVs. The electric engine is often positioned closely to the wheels of the electric car, which seems to affect various other design parameters of automobiles.

Although some design parameters in BEVs, such as speed (C), fueling/charging type (F), and engine type (J), lose dependencies compared to ICEVs, these design parameters gain new dependencies with other design parameters. Thus, even though the shift from ICEVs to BEVs seems to remove some dependencies, it appears to introduce new dependencies between the design parameters of automobiles. Overall, this corroborates our conclusion that BEVs are highly integrated technologies. Taken together, our findings suggest that while the power train of BEVs is structurally simpler than ICEVs, BEVs are slightly less modular than ICEVs.

5. The future architecture of the automotive industry

Based on our findings and the mirroring hypothesis, we will now derive predictions about the future architecture of the automotive industry focusing on firms involved in the manufacturing of automobiles. While we acknowledge that several factors, such as legal requirements (Jacobides *et al*., 2016), influence the architecture of the automotive industry, we primarily focus on the impact of the technological structure of BEVs on the architecture of the automotive industry. To add nuance to our predictions, we also draw on contextual knowledge of the automotive industry and briefly consider the influence of other innovations pertaining to automobiles (i.e., connectivity, autonomous driving, and mobility as a service) at the end (Teece, 2018).

5.1 Implications of the structurally simpler power train of BEVs and its shifted value distribution

Our findings show that the power train of BEVs is structurally simpler compared to the power train of ICEVs. Furthermore, our findings demonstrate that the most valuable module in ICEV power trains is the engine, whereas the most valuable module in BEV power trains is the fuel storage (i.e., the battery). While OEMs' power train design capabilities allowed them to solve and control this technical bottleneck of ICEVs and capture most of the value pertaining to the power train of ICEVs, the technological shift from ICEVs to BEVs renders their ICEV power train design capabilities largely irrelevant as BEV power trains are composed of very different technologies. That is, OEMs lose an important element of their architectural advantage, which we predict will have profound implications for the architecture of the automotive industry in the short term but not in the long term.[12]

In the automotive industry manufacturing ICEVs, OEMs design the power train, but suppliers manufacture most of its parts. Although the technological shift from ICEVs to BEVs renders OEMs' ICEV power train design capabilities largely irrelevant, the structural simplicity of BEV power trains should enable incumbent OEMs to transform their ICEV power train design capabilities into BEV power train design capabilities (Teece *et al.*, 1997; Teece, 2007). This transformation is likely somewhat aided by their previous expertise in ICEV power trains, which contributes to their absorptive capacity, enabling them to effectively and efficiently learn about the power train of BEVs (Cohen and Levinthal, 1990). ICEV incumbents do not face the huge challenges mechanical typewriter companies faced with the advent of electric typewriters and later computers leading to the demise of the leading typewriter firms (Danneels, 2011). Therefore, we expect that OEMs will also design the power train of BEVs (as Alochet *et al.* (2022) confirm for today), and suppliers will manufacture most of its parts in the future.

Even though we expect suppliers to manufacture most parts of BEV power trains in the future, they will have to supply radically different components to OEMs. But the suppliers of ICEV power train components have no easy option of becoming suppliers for BEV power train components as they would have to acquire mostly new capabilities, unless they possess exceptionally strong dynamic capabilities (Teece *et al.*, 1997; Teece, 2007). Hence, we expect to see a substantial decline in the market value of firms that supply components related to the fuel intake, fuel tank, engine, transmission, and exhaust modules of ICEV power trains. In parallel, we expect a substantial increase in the market value of firms that supply components related to the charge system, traction battery cells, electric power control unit, electric traction motor, and transmission modules of BEV power trains.

As the power train of BEVs consists of fewer first-order and second-order subsystems and assuming the economies of scale to be similar, we also predict that the number of firms supplying components for the power train of BEVs in steady state (e.g., 30 years from now) will be less than the number of firms currently supplying components for the power train of ICEVs. But if some suppliers succeed in transforming their ICEV power train manufacturing into BEV power train manufacturing capabilities, these suppliers may survive. Since the knowledge base of BEV power trains is so different from ICEV power trains, BEVs represent largely a competency-destroying rather than competency-enhancing innovation (Tushman and Anderson, 1986). Hence, we expect that the supply chain of BEV power trains will consist of mostly new BEV and only a few old ICEV suppliers who will develop the capabilities in the manufacturing of BEV power trains organically. The richest suppliers may buy up BEV power train start-ups, but the average supplier may not have the financial resources to make such an inorganic diversification.

Although the total value of a BEV power train is approximately the same compared to the total value of a (diesel) ICEV power train, the value distribution has shifted. While the engine is the most valuable part of the ICEV power train, the most valuable part of the BEV power train is the traction battery. This corresponds to the fact that the engine is the technical bottleneck of the ICEV power train, whereas the traction battery is the technical bottleneck of the BEV power train (Baldwin, 2015, 2018, 2019).[13] While OEMs solved and controlled the technical bottleneck of the engine in ICEV power trains, suppliers currently solve and control the technical bottleneck of the traction battery in BEV power trains. Incumbent OEMs manufacturing BEVs like VW, Mercedes-Benz, BMW, Toyota, and Honda currently do not have the capabilities to make their own batteries cells and instead buy their battery cells from suppliers like China's Contemporary

12 It is important to note that the radical structural change of the power train likely also implies that OEMs' legal and certification capabilities related to the power train of automobiles are rendered partially irrelevant. Therefore, OEMs likely have to develop the corresponding new legal and certification capabilities to fulfill the legal and regulatory requirements associated with the new power train of BEVs. However, as we do not have any systematic data on the impact of the technological shift from ICEVs to BEVs on OEMs' legal and certification capabilities that inform our predictions on the future architecture of the automotive industry, we do not discuss them further.

13 The traction battery represents the key bottleneck of BEVs because it limits the driving range of BEVs and causes long recharging breaks. Furthermore, traction batteries currently make BEVs more expensive than gasoline ICEVs as they are based on lithium-ion technology, which requires expensive rare earth elements limiting production capacities. For all these reasons, the race is on to develop alternative battery technologies that offer higher performance at lower prices, thus eliminating the price and performance gaps of BEVs compared to ICEVs (GlobalData Plc, 2020).

Amperex Technology (CATL) (Yang and Jin, 2019). In other words, battery suppliers control an important complementary asset in the BEV technology (Teece, 1986, 2006). OEMs' system integration capabilities remain relevant for BEVs, which increases OEMs' bargaining power. Some of the battery suppliers' current sources of bargaining power, such as China's policy forcing all OEMs building BEVs in China to buy battery cells from CATL, may not persist in the future. Thus, battery cell suppliers should still capture more value than previous ICEV and other BEV suppliers. Therefore, we predict that value will migrate from incumbent OEMs to suppliers of lithium-ion car battery cells during the next 5 years.

However, when value migrates from incumbent OEMs to suppliers, the incumbent OEMs will be incentivized to build up BEV power train design capabilities to solve and control the technical bottlenecks of BEV power trains. Just as they design and manufacture the most valuable parts of engines for ICEVs, establishing their BEV power train design capabilities would enable them to design and manufacture their own battery cells.[14] Thereby, OEMs could regain control of an important complementary asset in the BEV technology (Teece, 1986, 2006). This is already happening. For example, incumbent OEMs like VW are now investing in battery cell technology and production capacity. Specifically, VW plans to invest US $29 billion in European car battery stations and a network of charging stations (Rauwald, 2021). Furthermore, General Motors has begun to build capabilities allowing them to take over tasks related to the arrangement of battery cells, the incorporation of battery packs in battery platforms, and the battery management system. Despite these efforts, the PC industry offers a cautionary tale, suggesting that OEMs' attempt to build up battery cell manufacturing capabilities may be unsuccessful as the system integrators of PCs IBM and Motorola have been unsuccessful in their attempts to develop a reduced instruction chip to wrest market share away from the dominant integrated circuit producer Intel. Whether OEMs are able to succeed will partly depend on the Research & Development capabilities of battery cell suppliers, as these may determine whether they can stay ahead of OEMs and continue providing the best solution to the technical bottleneck, thus controlling it. But given OEMs' resources and the potential value that they can capture from battery cells, we predict that most incumbent OEMs will make large investments into building capabilities that allow them to control the battery system including battery cells.

5.2 Implications of the slightly less modular BEV at the system level

Our analyses of ICEV and BEV DSMs revealed that, contrary to what we expected, BEVs are slightly less modular than ICEVs at the system level, which means that the system integration requirements of BEVs are still high. Therefore, OEMs' system integration capabilities remain as relevant for the manufacturing of BEVs as they are for ICEVs. As BEVs appear to introduce new dependencies between design parameters, OEMs may even need to build up additional system integration capabilities to fulfill the system integration requirements of BEVs. However, OEMs are likely able to cope with new dependencies between design parameters because their knowledge as system integrators can enable them to deal with unexpected dependencies effectively (Brusoni *et al.*, 2001). Furthermore, previous experience with similar technologies like hybrid cars further facilitates the acquisition of relevant knowledge and, thus, the acquisition of the required system integration capabilities. That is, although system integration capabilities idiosyncratic to power trains become less relevant, it may also help in the acquisition of the idiosyncratic system integration capabilities for BEVs.

Taken together, this suggests that the most important element of OEMs' architectural advantage has not been eroded by the technological shift from ICEVs to BEVs (Jacobides *et al.*, 2016). In other words, BEVs do not represent an architectural innovation with potentially industry-revolutionizing effects (Henderson and Clark, 1990). Hence, OEMs will likely maintain their control of the architecture of the automotive industry. Beyond these implications for incumbent OEMs, the continued relevance of system integration capabilities has important implications for

14 Alochet *et al.* (2022: table 6) provide an excellent overview showing which incumbents and start-ups are presently producing their own battery packs from purchased battery cells and which source entire battery packs from suppliers. It is striking that while many incumbents make their battery packs in their home countries, they do not attempt this for the cars they produce in China. For a more detailed discussion of the pattern, see Alochet *et al.* (2022: section 6).

the question of whether or not BEV start-ups will gain significant market share in the automotive industry.

The technological shift from ICEVs to BEVs has attracted a host of BEV start-ups across the world. The most prominent start-ups come from the USA (Tesla, Lucid, and Rivian) and China (NIO, WM Motors, Xpeng Motors, Hozon, and BYD), where 500 new firms have registered to develop BEVs (Song *et al.*, 2019). These start-ups may have seen the first opportunity to enter the automotive industry with a reasonable chance of success in almost 100 years because they perceived BEVs to be more modular and the power train of BEVs to be structurally simpler compared to ICEVs (Perkins and Murmann, 2018). But while our findings suggest that the power train of BEVs is structurally simpler, BEVs are slightly less modular than ICEVs. Consequently, start-ups have to build up relevant system integration capabilities that incumbent OEMs already have and, in addition, have to acquire the power train design capabilities for BEVs.

Tesla and NIO have shown that start-ups can acquire these new capabilities in 3.5–5 years. Between its founding in November 2014 and June 2018, NIO developed an electric vehicle from scratch—the ES8 SUV—that impressed the auto world with its technical abilities and quality. This 3.5-year development time for a new car platform is faster than the 5–10 years premium incumbent ICEV automakers have historically taken to develop entirely new vehicles, and even faster than the 5 years Tesla took to develop and ship its Model S.[15] To achieve this short development time, NIO spent about US $2.3 billion while developing the ES8 SUV,[16] which is consistent with earlier research on Tesla's US $2 billion cost of developing an electric vehicle (Perkins and Murmann, 2018). But having not reached volume production and spending cash freely to develop high-quality cars, NIO faced bankruptcy in 2020 (Macroaxis, 2021) and had to be bailed out by capital infusion from a US $1 billion Chinese government entity. According to Elon Musk, Tesla also came close to bankruptcy during its ramp-up of its Model 3 production (Szymkowski, 2020). Although this highlights the challenge that start-ups need to continue finding investors who bankroll the ventures before they solidly break even,[17] this also shows that start-ups can acquire the power train design and system integration capabilities for BEVs if they possess sufficient financial resources.

Although start-ups can build the system integration and power train design capabilities for BEVs, there may not be sufficient market space for them to become significant players in the automotive industry in North America and Europe. Incumbent firms are now spending massive amounts of money to electrify their fleet—for example, VW is planning to spend US $177 billion on BEVs and software (Rauwald, 2020)—and new start-ups now face competition that Tesla never faced when it brought the Model S and more recently the Model 3 into the market. In the first quarter of 2021, there are already over 100 all-electric car models on sale in Europe (EV Genius LLC, 2020), and all major car companies will bring out BEVs in the various market segments. VW alone is planning to introduce 70 all-electric models by 2030 (Frangoul, 2021). Tesla is in a category by itself because, being the pioneer of BEVs, it has developed a brand that rivals the brand of incumbent luxury car makers like Mercedes, BMW, and Audi. NIO is trying to emulate Tesla's strategy of starting at the high-end premium market and then moving to the mass market. Underserved markets that Tesla could exploit to build up sales will disappear quickly in the next few years. But it is not clear that there is still market space to do this now that incumbent premium players are rolling out their BEVs. The fact that Tesla and NIO were able to build the system integration and power train design capabilities for BEVs from scratch also suggests that incumbent OEMs will succeed in their efforts to transition from ICEVs to BEVs. Therefore, we

15 One reviewer pointed out that "Toyota needs 18-24 months to develop a new product or major redesign, less for a minor refresh." It took VW roughly 4 years to bring out an electric car (the ID3) based on a new electric platform, and it is clearly faster to produce additional variants (e.g., the ID4) on the same platform. Established OEMs now want to speed up their development times to hold start-ups at bay.

16 Among others, NIO spent this money on building research centers in Silicon Valley, Oxford, and Munich to access and lure away talent from incumbent firms that it could not find in China to speed up their learning of how to design technologically advanced and safe automobiles.

17 To be fair, incumbent OEMs also face the challenges of financing the shift to BEVs, but incumbent firms—as long as they are profitable—can raise money from their legacy operations. For example, as the CEO of VW outlined in a speech to all employees, VW will make substantial profits with ICEVs in the next years to pay for its BEV strategy (Diess, 2020). And some ICEV incumbents are listing parts of the assets as separate units on the stock market to raise new cash for their BEV investments.

expect that the establishment of Tesla as an OEM will remain the notable exception in North America and Europe and that there will be a shakeout among BEV start-ups in the next decade similar to one that students of the early automobile industry documented for the period after 1905 that led to a massive reduction of firms in the industry (Klepper and Simons, 1996). Furthermore, we predict that, in North America and Europe except for Tesla, no massive value migration will take place from ICEV OEM to BEV OEM start-ups.

5.3 Implications of CAS innovations

In addition to the electrification of automobiles, the CAS innovations (i.e., innovations related to connectivity, autonomous driving, and mobility as a service) pertaining to automobiles will influence the future architecture of the automotive industry (Teece, 2018). The increased connectivity of cars will represent an opportunity for tech giants like Alphabet, Apple, and Alibaba to participate in the automotive industry by providing software that will connect the car to various services in the cloud, which may allow them to capture value through new or complementary business models in the automotive industry (Teece, 2018). The push for autonomous driving will be influential in this regard. While tech giants may not use their massive cash reserves to start or buy an OEM (Jiang and Lu, 2018), they will continue investing in car operating systems and autonomous driving software that will be part of the "brain" controlling future BEVs. A few OEMs have also started investing in software capabilities to create autonomous driving software, with Alphabet's Waymo currently in the lead. Therefore, we expect that some value will migrate from OEMs to tech giants like Alphabet, Apple, and Alibaba. The magnitude of this value migration will depend partly on (i) whether one or multiple providers of autonomous driving technology will exist (Adner and Lieberman, 2021) and (ii) whether incumbent OEMs can build competitive car operating software themselves (as VW and Mercedes-Benz are presently trying). If multiple providers of autonomous driving technology will exist and OEMs can build competitive car operating software themselves, little value will migrate to tech giants. As OEMs likely prefer to build software themselves to maintain full control of the architecture of the automotive industry, we expect that most incumbent OEMs will increase their investment in their software capabilities dramatically and try to secure access to functionally competitive self-driving technology. Lastly, even though mobility as a service may have the potential to decrease the overall value that can be captured in the automotive industry, as ridesharing services like Uber, carsharing services like Car2Go, and car subscription services like Porsche Drive reduce the need to own a car, we expect that mobility as a service will not change the architecture of the automotive industry.

6. Discussion

We began our paper with the conjecture that the technological shift from ICEVs to BEVs may render OEMs' power train design and system integration capabilities partly irrelevant because BEVs seem to be structurally simpler and more modular compared to ICEVs. As their system integration and power train design capabilities represent the primary source of OEMs' architectural advantage, which allows them to control the architecture of the automotive industry, the technological shift from ICEVs to BEVs seems to have the potential to upend the established architecture of the automotive industry. Therefore, we asked how the technological shift from ICEVs to BEVs will change the architecture of the automotive industry. To systematically investigate our research question, we analyzed the relative complexity of the power trains and the relative modularity of ICEVs and BEVs using DSMs.

We found that while the power train of BEVs is structurally simpler compared to the power train of ICEVs, contrary to widespread expectation BEVs are slightly *less* modular than ICEVs. This suggests that the technological shift from ICEVs to BEVs renders OEMs' ICEV power train design capabilities largely irrelevant, whereas OEMs' system integration capabilities, which are considered to be the most important element of OEMs' architectural advantage, remain highly relevant for BEVs. Drawing on our findings and the mirroring hypothesis, we therefore predict that changes in the architecture of the automotive industry will be confined to short-term changes pertaining to the structural simplicity and shifted value distribution of the BEV power train. In the following, we discuss the theoretical implications, limitations, and future research opportunities pertaining to our research.

6.1 Theoretical implications

The key assumption underlying modularity theory is that modular technologies have several advantages over integrated technologies. Modularity allows for the partitioning of knowledge (Takeishi, 2002), which facilitates the independent specialization of persons, groups, and organizations. This creates value for firms because it enables efficient transactions (Baldwin, 2008), allows for independent technological innovations, and conserves scarce cognitive resources (Colfer and Baldwin, 2016). Furthermore, firms can use modularity strategically to hide information (Parnas, 1972) and protect intellectual property (Baldwin and Henkel, 2015). As this practice can permit firms to produce innovative products at a low cost, modularity can create value for customers. These advantages seem to make modularity the desirable technology structure (Sanchez and Mahoney, 1996) and also induce integrated technologies to modularize over time (Schilling and Steensma, 2001; MacDuffie, 2013). The result is industry architectures in which specialized firms that solve and control the technical bottlenecks of a technology capture the lion's share of the value (Baldwin and Clark, 2000; Jacobides, 2005; Argyres and Bigelow, 2010). The PC has been the prototypical case supporting this reasoning (Langlois and Robertson, 1992; Baldwin and Clark, 2000).

In contrast, our research suggests that some technologies remain persistently integrated. One explanation for this may be that the value of integrated technologies may outweigh the potential value of modular technologies if customers are willing to pay for a well-integrated technology and the market for this well-integrated technology is large enough. Automobiles may be one case supporting this reasoning (see also Alochet *et al.*, 2022). A well-integrated automobile and the brand associated with it create a "look and feel" (Jacobides *et al.*, 2016: 1958) that is valued and, thus, paid for by customers. The CAS innovations will likely further amplify the importance of providing a well-integrated automobile that provides a unique driving experience as connectivity, autonomous driving, and mobility as a service will need to be closely integrated with the other design parameters of automobiles to create the desired driving experience (Teece, 2018). For example, entertainment systems may increase in importance when automobiles will drive autonomously.

In the industries of such integrated technologies, system integration capabilities allow firms to determine the division of labor and capture the lion's share of the value as they are able to solve and control an important technical bottleneck of the technology (Baldwin, 2015, 2018, 2019). Even when innovations occur at the subsystem level, firms that possess system integration capabilities may be able to profit from this innovation as long as the fundamental architecture of the technology remains intact (Teece, 1986, 2006; Henderson and Clark, 1990). Ultimately, systems integrators' knowledge can enable them to deal with unexpected dependencies of new technologies effectively (Brusoni *et al.*, 2001). Therefore, the potential inefficiencies related to integrated technologies resulting from the requirement for system integrators to "know more than they make" (Brusoni *et al.*, 2001: 597) to effectively coordinate the actors and activities involved in the manufacturing of the integrated technology (Brusoni and Prencipe, 2001) may be outweighed by the gains deriving from serving markets demanding integrated technologies. In other words, value may lie at the other end of the modularity continuum (Schilling, 2000), which firms may be able to deliberately exploit through strategic choice (Cabigiosu *et al.*, 2013; Jacobides and MacDuffie, 2013). This could explain why integrated technologies and integrated industry architectures in the automotive industry and other industries persist (e.g., Fixson and Park, 2008). More generally, this highlights the importance of technology design as a mechanism to capture value (Sharapov and MacAulay, 2022).

6.2 Limitations and future research opportunities

Our findings are based on data from two incumbent OEMs and one BEV start-up. One challenge of investigating the structure of technologies that are not amenable to direct analysis like computer software (cf. MacCormack *et al.*, 2006, 2012) is the time and effort required for the creation of DSMs. Previously, researchers investigated the structure of such technologies by creating and filling in the DSMs themselves based on interviews with their informants (e.g., Sosa *et al.*, 2020). In contrast, we closely collaborated with four engineers who created, validated, and filled in the DSMs. Although this meant a considerable time investment for our informants (one DSM took one respondent on average 5 h), this ensured the highest possible data quality and, therefore, represents an improvement over the previous research approach.

Ideally, one would collect data from many knowledgeable informants and many different automobile firms to ensure that objective design dependencies rather than subjective mental models drive the DSM evaluations of the informants. Averaging the evaluations of the informants within each firm would approximate the true DSM for ICEV and BEV of the corresponding firm; averaging the corresponding DSMs across all automobile firms would approximate the DSM for ICEV and BEV, which could be used to evaluate whether BEVs are more modular than ICEVs on average. Variations from this average would represent actual differences in the design of ICEVs and BEVs. While this approach would be optimal, we found that many automobile companies regard DSM data as too sensitive to share them with external researchers.

In this light, our research represents an important first step to accomplishing this ideal as our purposive sample allowed us to *explore* the design structure and modularity of ICEVs and BEVs. In so doing, we falsified our conjecture that BEVs are more modular than ICEVs (Popper, 1959). Given that we disconfirmed our main conjecture, took measures to validate our data, and found our results to be consistent across all firms despite variability in the estimates of the dependencies between the design parameters of automobiles, we trust our conclusions. But the confidence in our findings will further increase if future research independently confirms our findings by collecting additional data from engineers working at incumbent OEMs and start-ups. In particular, BEV start-ups building their business case on the idea that it is easier to become an OEM with BEVs can use our methodology to calculate whether their designs are truly more modular than ICEVs and can then share their findings publicly.

Although the structure of a technology is an important factor determining the architecture of an industry, other factors also need to be acknowledged. Most importantly, the future architecture of the automobile industry will also depend on the regulatory requirements imposed on the industry (Jacobides *et al.*, 2016). Our results suggest that the structurally simpler power train of BEVs also renders the legal and certification capabilities related to the power train of ICEVs largely irrelevant. Therefore, OEMs likely have to acquire the corresponding new legal and certification capabilities to fulfill the legal and regulatory requirements associated with the new power train of BEVs. Future research should, therefore, examine systematically how the technological shift from ICEVs to BEVs affects the legal and certification capabilities of automobile firms. Examining this impact requires a different methodological approach (e.g., via interviews with employees who are responsible for the certification of parts to comply with legal requirements), which is beyond the scope of this paper. Furthermore, complements, such as the availability of the charging infrastructure, may influence the speed at which the technological shift from ICEVs to BEVs is going to happen and also influence the architecture of the automotive industry (Adner and Lieberman, 2021). However, analyzing the impacts of these factors is beyond the scope of this paper and hence represents an opportunity for additional research efforts. Moreover, future research clearly needs to investigate the impact of innovations related to the connectivity of automobiles, autonomous driving, and mobility as a service (Teece, 2018) on the architecture of the automotive industry in a more systematic fashion.

To conclude, our findings suggest that the technological shift from ICEVs to BEVs renders OEMs' ICEV power train design capabilities largely irrelevant, whereas OEMs' system integration capabilities will remain as relevant for BEVs as they are for ICEVs. Therefore, we predict that changes in the architecture of the automotive industry will be confined to short-term changes pertaining to the structural simplicity and shifted value distribution of BEV power trains. In the long term, we expect that OEMs will reestablish a similar degree of control over the architecture of the automotive industry manufacturing BEVs as they have established over the architecture of the automotive industry manufacturing ICEVs. Furthermore, we predict that, except for Tesla, start-up OEMs in North America and Europe will not be able to compete away value from incumbent OEMs. In these times of profound industry change, the continued relevance of system integration capabilities for manufacturing BEVs represents a silver lining for incumbent OEMs.

Supplementary Data

Supplementary data are available at *Industrial and Corporate Change* online.

Acknowledgement

We embarked on this project to honor the scholarly contribution of Carliss Baldwin and Kim Clark. This study only became possible because of the anonymous informants who generously gave their time to provide us with the key data of our study for which we are very grateful.

References

Adner, R. and M. Lieberman (2021),'Disruption through complements,' *Strategy Science*, **6**(1), 91–109.

Alochet, M., J. P. MacDuffie and C. Midler (2022), 'Mirroring in production? Early evidence from the scale-up of battery electric vehicles (BEVs),' *Industrial and Corporate Change*.

Argyres, N. and L. Bigelow (2010), 'Innovation, modularity, and vertical deintegration: evidence from the early U.S. auto industry,' *Organization Science*, **21**(4), 842–853.

Baldwin, C. Y. (2008), 'Where do transactions come from? Modularity, transactions, and the boundaries of firms,' *Industrial and Corporate Change*, **17**(1), 155–195.

Baldwin, C. Y. (2015), 'Bottlenecks, Modules and Dynamic Architectural Capabilities,' *SSRN Scholarly Paper ID 2512209*. Social Science Research Network: Rochester. https://papers.ssrn.com/abstract=2512209. (Accessed January 22, 2021).

Baldwin, C. Y. (2018), 'Design Rules, Volume 2: How Technology Shapes Organizations: Chapter 7— The Value Structure of Technologies, Part 2: Technical and Strategic Bottlenecks as Guides for Action,' *SSRN Electronic Journal*. https://www.ssrn.com/abstract=3270955. (Accessed May 12, 2020).

Baldwin, C. Y. (2019), 'Design Rules, Volume 2: How Technology Shapes Organizations: Chapter 16—Capturing Value by Controlling Bottlenecks in Open Platform Systems,' *SSRN Electronic Journal*. https://www.ssrn.com/abstract=3482538. (Accessed May 12, 2020).

Baldwin, C. Y. and K. B. Clark (2000), *Design Rules*, Vol. 1. MIT Press: Cambridge.

Baldwin, C. Y. and J. Henkel (2015), 'Modularity and intellectual property protection,' *Strategic Management Journal*, **36**(11), 1637–1655.

Baldwin, C. Y., A. MacCormack and J. Rusnak (2014), 'Hidden structure: using network methods to map system architecture,' *Research Policy*, **43**(8), 1381–1397.

Bartko, J. J. (1966), 'The intraclass correlation coefficient as a measure of reliability,' *Psychological Reports*, **19**(1), 3–11.

Brusoni, S. and A. Prencipe (2001), 'Unpacking the black box of modularity: technologies, products and organizations,' *Industrial and Corporate Change*, **10**(1), 179–205.

Brusoni, S., A. Prencipe and K. Pavitt (2001), 'Knowledge specialization, organizational coupling, and the boundaries of the firm: why do firms know more than they make?' *Administrative Science Quarterly*, **46**(4), 597–621.

Cabigiosu, A. and A. Camuffo (2012), 'Beyond the "mirroring" hypothesis: product modularity and interorganizational relations in the air conditioning industry,' *Organization Science*, **23**(3), 686–703.

Cabigiosu, A., F. Zirpoli and A. Camuffo (2013), 'Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry,' *Research Policy*, **42**(3), 662–675.

Christensen, C. (1997), *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business Review Press: Boston.

Cohen, W. M. and D. A. Levinthal (1990), 'Absorptive capacity: a new perspective on learning and innovation,' *Administrative Science Quarterly*, **35**(1), 128–152.

Colfer, L. J. and C. Y. Baldwin (2016), 'The mirroring hypothesis: theory, evidence, and exceptions,' *Industrial and Corporate Change*, **25**(5), 709–738.

Danneels, E. (2011), 'Trying to become a different type of company: dynamic capability at Smith Corona,' *Strategic Management Journal*, **32**(1), 1–31.

Diess, H. (2020), 'Autokonzern im Wandel: VW-Chef Diess: "Wenn wir in Unserem Jetzigen Tempo Weitermachen, Wird es sehr eng",' https://www.handelsblatt.com/unternehmen/industrie/autokonzern-im-wandel-vw-chef-diess-wenn-wir-in-unserem-jetzigen-tempo-weitermachen-wird-es-sehr-eng/25441126.html. (Accessed May 2, 2021).

Eppinger, S. D. and T. R. Browning (2012), *Design Structure Matrix Methods and Applications*. MIT Press: Cambridge.

Eppinger, S. D., D. E. Whitney, R. P. Smith, *et al.* (1994), 'A model-based method for organizing tasks in product development,' *Research in Engineering Design*, **6**(1), 1–13.

EV Genius LLC. (2020), 'European EV Price List | Price List of Electric Cars in EUROPE | WattEV2Buy,' https://wattev2buy.com/european-ev-market-price-list-electric-cars-eu/. (Accessed May 2, 2021).

Fixson, S. K. and J.-K. Park (2008), 'The power of integrality: linkages between product architecture, innovation, and industry structure,' *Research Policy*, **37**(8), 1296–1316.

Frangoul, A. (2021), 'Daimler's Mercedes-Benz Triples its Electric Car Sales as CEO Predicts a 'Transformative' Decade,' *CNBC*. https://www.cnbc.com/2021/01/08/daimlers-mercedes-benz-triples-electric-car-sales.html. (Accessed May 2, 2021).

Fredriksson, G., A. Roth, S. Tagliapietra and R. Veugelers (2018), 'Is the European Automotive Industry Ready for the Global Electric Vehicle Revolution?' https://www.bruegel.org/sites/default/files/wp_attachments/PC-26_2018_1.pdf. (Accessed August 20, 2022).

GlobalData Plc. (2020), 'Alternative Battery Technologies Crucial for Sustainable Transportation, Says GlobalData,' *GlobalData*. 23 October. https://www.globaldata.com/alternative-battery-technologies-crucial-sustainable-transportation-says-globaldata/. (Accessed May 2, 2021).

Henderson, R. M. and K. B. Clark (1990), 'Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms,' *Administrative Science Quarterly*, **35**(1), 9–30.

Jacobides, M. G. (2005), 'Industry change through vertical disintegration: how and why markets emerged in mortgage banking,' *Academy of Management Journal*, **48**(3), 465–498.

Jacobides, M. G., T. Knudsen and M. Augier (2006), 'Benefiting from innovation: value creation, value appropriation and the role of industry architectures,' *Research Policy*, **35**(8), 1200–1221.

Jacobides, M. G. and J. P. MacDuffie (2013), 'How to drive value your way,' *Harvard Business Review*, **91**(7/8), 92–100.

Jacobides, M. G., J. P. MacDuffie and C. J. Tae (2016), 'Agency, structure, and the dominance of OEMs: change and stability in the automotive sector,' *Strategic Management Journal*, **37**(9), 1942–1967.

Jacobides, M. G. and C. J. Tae (2015), 'Kingpins, bottlenecks, and value dynamics along a sector,' *Organization Science*, **26**(3), 889–907.

Jiang, H. and F. Lu (2018), 'To be friends, not competitors: a story different from tesla driving the chinese automobile industry,' *Management and Organization Review*, **14**(3), 491–499.

Klepper, S. and K. L. Simons (1996), 'Innovation and industry shakeouts,' *Business and Economic History*, **25**(1), 81–89.

Langlois, R. N. (2002), 'Modularity in technology and organization,' *Journal of Economic Behavior & Organization*, **49**(1), 19–37.

Langlois, R. N. and P. L. Robertson (1992), 'Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries,' *Research Policy*, **21**(4), 297–313.

Leach, S. (2021), 'Electric Vehicle Patents Rise, Fossil Fuel Vehicle Patents Fall as 2030 Zero-Emission Deadline Gets Closer,' https://www.mathys-squire.com/insights-and-events/news/electric-vehicle-patents-rise-fossil-fuel-vehicle-patents-fall-as-2030-zero-emission-deadline-gets-closer/. (Accessed August 20, 2022).

Leggett, D. (2021), 'Could Toyota Become the New King of EV Innovation?' https://www.just-auto.com/analysis/could-toyota-become-the-new-king-of-ev-innovation/. (Accessed August 20, 2021).

MacCormack, A., C. Baldwin and J. Rusnak (2012), 'Exploring the duality between product and organizational architectures: a test of the "mirroring" hypothesis,' *Research Policy*, **41**(8), 1309–1324.

MacCormack, A., J. Rusnak and C. Y. Baldwin (2006), 'Exploring the structure of complex software designs: an empirical study of open source and proprietary code,' *Management Science*, **52**(7), 1015–1030.

MacDuffie, J. P. (2013), 'Modularity-as-property, modularization-as-process, and "modularity"-as-frame: lessons from product architecture initiatives in the global automotive industry: modularity-as-property, modularization-as-process, and "modularity"-as-frame,' *Global Strategy Journal*, **3**(1), 8–40.

Macroaxis, L. L. C. (2021), 'What is NIO Probability Of Bankruptcy? (NYSE:NIO),' *Macroaxis*. https://www.macroaxis.com/invest/ratio/NIO/Probability-Of-Bankruptcy#. (Accessed May 2, 2021).

McGraw, K. O. and S. P. Wong (1996), 'Forming inferences about some intraclass correlation coefficients,' *Psychological Methods*, **1**(1), 30–46.

Murmann, J. P. and K. Frenken (2006), 'Toward a systematic framework for research on dominant designs, technological innovations, and industrial change,' *Research Policy*, **35**(7), 925–952.

Parnas, D. L. (1972), 'On the criteria to be used in decomposing systems into modules,' *Communications of the ACM*, **15**(12), 1053–1058.

Perkins, G. and J. P. Murmann (2018), 'What does the success of tesla mean for the future dynamics in the global automobile sector?' *Management and Organization Review*, **14**(3), 471–480.

Pisano, G. P. and D. J. Teece (2007), 'How to capture value from innovation: shaping intellectual property and industry architecture,' *California Management Review*, **50**(1), 278–296.

Popper, K. R. (1959), *The Logic of Scientific Discovery*. Basic Books: New York.

Rauwald, C. (2020), 'VW Boosts Tech Spending Within $177 Billion Investment Plan,' *Bloomberg.com*. 13 November. https://www.bloomberg.com/news/articles/2020-11-13/vw-boosts-tech-spending-in-177-billion-budget-amid-virus-hit. (Accessed May 2, 2021).

Rauwald, C. (2021), 'VW Plans to Be Battery Juggernaut in $29 Billion Answer to Tesla', *Bloomberg.com*. 15 March. https://www.bloomberg.com/news/articles/2021-03-15/vw-plans-europe-s-biggest-battery-push-in-electric-offensive. (Accessed May 2, 2021).
Sako, M. (2004), 'Supplier development at Honda, Nissan and Toyota: comparative case studies of organizational capability enhancement,' *Industrial and Corporate Change*, **13**(2), 281–308.
Sanchez, R. and J. T. Mahoney (1996), 'Modularity, flexibility, and knowledge management in product and organization design,' *Strategic Management Journal*, **17**(S2), 63–76.
Schilling, M. A. (2000), 'Toward a general modular systems theory and its application to interfirm product modularity,' *Academy of Management Review*, **25**(2), 312–334.
Schilling, M. A. and H. K. Steensma (2001), 'The use of modular organizational forms: an industry-level analysis,' *Academy of Management Journal*, **44**(6), 1149–1168.
Sharapov, D. and S. C. MacAulay (2022), 'Design as an isolating mechanism for capturing value from innovation: from cloaks and traps to sabotage,' *Academy of Management Review*, **47**(1), 139–161.
Shrout, P. E. and J. L. Fleiss (1979), 'Intraclass correlations: uses in assessing rater reliability,' *Psychological Bulletin*, **86**(2), 420–428.
Simon, H. A. (1962), 'The architecture of complexity,' *Proceedings of the American Philosophical Society*, **106**(6), 467–482.
Song, N., H. Suzuki and M. Aou (2019), 'Will Chinese EV Start-Ups Reshape the Automotive Industry?' https://www.adlittle.com/en/insights/viewpoints/will-chinese-ev-start-ups-reshape-automotive-industry. (Accessed May 2, 2021).
Sosa, M. E., S. D. Eppinger and C. M. Rowles (2020), 'Designing Modular and Integrative Systems,' *American Society of Mechanical Engineers Digital Collection*. 303–312. https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings/IDETC-CIE2000/35142/303/1093613. (Accessed September 22, 2021).
Steward, D. V. (1981), 'The design structure system: a method for managing the design of complex systems,' *IEEE Transactions on Engineering Management*, **28**(3), 71–74.
Sturgeon, T. J. (2002), 'Modular production networks: a new American model of industrial organization,' *Industrial and Corporate Change*, **11**(3), 451–496.
Szymkowski, S. (2020), Tesla Bankruptcy? It Nearly Happened Amid Model 3 Scale-Up, Elon Musk Reveals, *Roadshow*. https://www.cnet.com/roadshow/news/tesla-bankruptcy-it-nearly-happened-amid-model-3-scale-up-elon-musk-reveals/. (Accessed May 2, 2021).
Takeishi, A. (2002), 'Knowledge partitioning in the interfirm division of labor: the case of automotive product development,' *Organization Science*, **13**(3), 321–338.
Teece, D. J. (1986), 'Profiting from technological innovation: implications for integration, collaboration, licensing and public policy,' *Research Policy*, **15**(6), 285–305.
Teece, D. J. (2006), 'Reflections on "profiting from innovation",' *Research Policy*, **35**(8), 1131–1146.
Teece, D. J. (2007), 'Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance,' *Strategic Management Journal*, **28**(13), 1319–1350.
Teece, D. J. (2018), 'Tesla and the reshaping of the auto industry,' *Management and Organization Review*, **14**(3), 501–512.
Teece, D. J., G. Pisano and A. Shuen (1997), 'Dynamic capabilities and strategic management,' *Strategic Management Journal*, **18**(7), 509–533.
Tee, R., A. Davies and J. Whyte (2019), 'Modular designs and integrating practices: managing collaboration through coordination and cooperation,' *Research Policy*, **48**(1), 51–61.
Tushman, M. L. and P. Anderson (1986), 'Technological discontinuities and organizational environments,' *Administrative Science Quarterly*, **31**(3), 439–465.
Tushman, M. L. and J. P. Murmann (1998), 'Dominant designs, technology cycles and organizational outcomes,' in B. Staw and L. Cummings (eds), *Research in Organizational Behavior*. JAI Press: Greenwich, pp. 231–266.
Ulrich, K. (1995), 'The role of product architecture in the manufacturing firm,' *Research Policy*, **24**(3), 419–440.
Williamson, O. E. (1975), *Markets and Hierarchies: Analysis and Antitrust Implications*. Free Press: New York.
Williamson, O. E. (1981), 'The economics of organization: the transaction cost approach,' *American Journal of Sociology*, **87**(3), 548–577.
Windrum, P., M. Haynes and P. Thompson (2019), "'Breaking the mirror": interface innovation and market capture by Japanese professional camera firms, 1955-1974,' *Industrial and Corporate Change*, **28**(5), 1029–1056.
Yang, H. and H. Jin (2019), 'Factbox: The World's Biggest Electric Vehicle Battery Makers,' *Reuters*. 26 November. https://www.reuters.com/article/us-autos-batteries-factbox-idUSKBN1Y02JG. (Accessed May 2, 2021).
Yoo, Y., O. Henfridsson and K. Lyytinen (2010), 'The new organizing logic of digital innovation: an agenda for information systems research,' *Information Systems Research*, **21**(4), 724–735.