Revisiting the role of modular innovation in technological radicalness and architectural change of products: The case of Tesla X and Roomba

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Revisiting the role of modular innovation in technological radicalness and architectural change of products: The Case of Tesla X and Roomba

The management literature defines modular innovation as a way to make technological changes in product modules that does not necessarily change the product architecture. However, engineering science shows that new product modules not only change the product architecture, but they can also be used for technologically radical next generation products. Therefore, there seems to be a misalignment in how the role of modular innovation is seen as an innovation management phenomenon and the actual practice of product design and engineering. We revisit the role of modular innovation by combining management and engineering approaches. We demonstrate the applicability of this approach through two cases that utilize patent data of two recent technologically innovative products: Tesla's Model X and iRobot's Roomba automated vacuum cleaner. The examples show, in detail, how the changes in product modules and functions have led to broader changes at the system architecture level, leading to new functionalities. The findings contribute to the innovation management literature by identifying a more nuanced role of modular innovation by embedding it in the product architecture, thus broadening the discussion on architectural innovation and technological radicalness.

Keywords: *Modular innovation, Architectural innovation, Radical innovation, System architecting, Product design, Technology*

1. Introduction

Rapid changes in technologies embedded in broader product architectures (such as nanotechnology, battery technology, artificial intelligence) represent an important mechanism for technological innovation. This can be labelled as *modular innovation*, referring to how new technology is introduced in specific components or subsystems of products. In contrast, *architectural innovation* occurs when new linkages between existing components or subsystems are made. From a product innovation perspective, both modular and architectural innovation can relate to technological newness or innovation radicalness. However, whereas architectural innovation can be viewed as an enabler for entirely new design standards in industries (Baldwin & Clark, 2006), the impact made by modular innovations is seen as more modest. For instance, Hofman et al. (2016) argue that modular innovation is contingent on existing design rules (which derive from the product architecture), whereas architectural innovation challenges and potentially changes the design rules (Henderson & Clark, 1990; see also; Hofman et al., 2016). The widely adopted definition of modular innovation by Henderson and Clark has guided how the management literature (see e.g., Aspelund et al., 2005; Cebon et al., 2008; Chen & Liu, 2005; Chou et al., 2016; den Hartigh et al., 2016; Magnusson et al., 2003; Sushandoyo & Magnusson, 2012; Xie et al., 2016) views the phenomenon of 'modular innovation …[which] is an innovation that changes a core design concept [by inserting a new technology in a module] without changing the product's architecture (1990, p. 12)'.

The seminal work of Henderson & Clark (1990) has paid particular attention to the notion of modular and architectural innovation when discussing the types of technological change. Like other authors, Henderson and Clark (1990: 11), have used incremental innovation and radical innovation as bookends to describe the impact on components (i.e., in explaining modular innovation) and linkages between components (i.e., explaining architectural innovation). A core notion in their work is that incremental innovation is associated with unchanged linkages between concepts and components, as well as reinforcing core concepts. In contrast, radical innovation is associated with changed linkages between concepts and components, as well as overturning core concepts. The notion of modular innovation (overturned components) and architectural innovation (change in linkages between core concepts and components) has provided a wholly new understanding of why some firms in particular struggled to adapt to architectural innovation. Henderson and Clark (1990: 12) further argued that, for architectural innovation, '*the core design concept behind each component – and the associated scientific and engineering knowledge – remain the same'*. This assertion was supported by a classic example of ceiling and portable fans (Henderson and Clark 1990: 12). These findings – and the management research that adopted the resulting conceptualizations – have made a valuable contribution to the modular and architectural innovation literature. However, previous findings have not focused on the micro-foundations of modular and architectural innovation nor has it attempted to explain when or under what circumstances modular and architectural innovation lead to radical or incremental innovation.

In fact, given that modular technologies, such as a behaviour system for autonomous vacuum cleaners, are quickly developing and being adapted into an increasing number of product categories, we argue that revisiting the role of modular innovation as a driver of technological innovation is paramount. We further argue that there are benefits to closely examining the interplay between modular and architectural innovation as a driver of technological radicalness. As mentioned above, these issues have not been thoroughly examined in the existing literature due to a tendency to establish distinct and separate roles for modular and architectural innovation (e.g., Chen & Liu, 2005; Chou et al., 2016; Magnusson et al., 2003;). However, some research is beginning to show that such a division of these roles might not be so clear-cut. For instance, previous research has investigated how different levels of modularity can affect product performance (in particular in relation to incremental innovation) (e.g., Ethiraj et al., 2008). Other studies indicate that changes in some components might be a trigger for architectural innovation (e.g., Carayannopoulos, 2009). However, the mechanisms of how both modular and architectural innovation interact at the actual level of product design – and how they eventually lead to technological radicalness – is still largely under-investigated.

To bridge the above-mentioned research gaps, in this study we examine how individual modules can have such a degree of novelty that they eventuate in new product architecture. By combining management and engineering perspectives and examining the technological change that takes place at the component/module level of a product, we can gain a deeper understanding into the core of a product and explore how individual modules have enabled new functionalities for the market (see also Smith, 2009; Tidd & Bessant, 2009). By carrying out a comparative case study on two technologically novel products, (1) Roomba's autonomous vacuum cleaning (VC) robot and (2) Tesla's Model X, we carefully examine how technological newness in these products' modules brings about novel functions of the product. Using patent data, product manuals and system architecting, we identify the design evolution in these products. The analysis reveals that modular innovation (i.e., technological newness in modules) affects the design and architecture of the product (i.e., interface and structure) by establishing different types of interfaces between the modules.

Our paper contributes to the existing literature as it looks into the *micro-foundations* and *interrelationships* between modular and architectural innovation. In doing so, it provides a deeper understanding into how some technological innovations deriving from the modular innovation (i.e., due to technological newness) and impact a product's architecture (i.e., architectural innovation), which ultimately leads to a radical technological innovation or incremental innovation. This dynamic is explained based on the case studies of the Tesla Model X and iRobot Roomba. The aim of the further investigation into modular and architectural innovation is thus to provide additional nuance into some of the dynamics at play in new product development, which can offer new insight into the management literature drawing from the seminal work of Henderson and Clark (1990). In this regard, our paper also presents a thorough understanding and conceptualization of modular and architectural innovation, and how they are related to radical and incremental innovation by combining engineering and management perspectives.

We argue that a deeper understanding of the technological modules of a product can enable innovation managers to better articulate exactly where a firm's core strengths in technological development lie, and how can they translate that technological change into customer utilities. Firms can then build and base new product functions on this understanding. Thus, in our empirical examinations, we focus on 'what the product is' and how some selective modules have been changed with new technologies that affected the entire architecture and function of the product. Building on this view, we argue that unique product functions are based on technological novelties in individual product modules. Overall, a more detailed understanding of product architectures—as portrayed in this study—will be helpful in providing a more pragmatic and applicable perspective to the interplay between modular and architectural innovation. Furthermore, our study also contributes to the innovation management literature by fostering a more dynamic view of various types of product innovation and their mutual interdependence.

The next section reviews the major concepts of this study and develops a conceptual framework. We then present the methodological design of the study, followed by the results and analysis. Then, we present a discussion and conceptualization of the relationship between modules, architecture and functions of innovations as well as managerial implications. We conclude by discussing limitations and areas for future research.

2. Modular and architectural product innovation: Management and engineering approaches

Modular and architectural innovation are concepts used to explain product innovation in the innovation management literature (e.g., Chen & Liu, 2005; Magnusson et al., 2003). However, these phenomena are also examined in engineering sciences in the form of product and product architecture research. While the management approach offers insights into the strategic importance of the two types of innovation, the engineering approach explains the roles of the two approaches in technological novelty as well as functionalities. Therefore, in this study, we argue that both approaches (engineering and management) are needed to fully understand the interplay between them and the role of each in technological radicalness and potential value creation for customers.

In both the management and engineering approaches, concepts such as modules in product development and the introduction of technology in modules are discussed. Furthermore, both approaches describe how these modules bring new functionality to products and discuss the changes in the architecture of the system. However, the management approach is primarily concerned with organizational aspects such as reconfiguring existing components in a new way to address market changes. The engineering approach, on the other hand, is more concerned with design issues, decomposition of the system, interface development and improvements in the core design system. Therefore, the engineering perspective complements the management approach by enabling a deeper understanding of product design and by supporting exploration of how individual modules have enabled radical changes that provide new functionalities for the market. These interplays will be discussed later in the empirical part of this study.

Table 1 below provides the definitions of modular and architectural innovation from both management and engineering points of view. As demonstrated in the table, the management approach views the phenomena from an aggregated level, while the engineering approach examines these issues from a product and product design level. We will discuss the relevant foundations and implications of both the approaches in the following sub-sections.

Management approach		**Engineering approach**	
Modular innovation (Henderson & Clark, 1990; Magnusson et al., 2003; Sköld & Karlsson, 2013)	[The technological] 'improvement occurs in individual components but the underlying core design concepts and the links between them remain the same' (Henderson & Clark, 1990, p. 11) The unit of analysis is the technology newness at the modules level.	**Modules, modularity and function** (Gershenson et al., 2003, Hubka & Eder, 1988; Pahl & Beitz, 1984; Pimmler & Eppinger, 1994)	A module is a physical or conceptual grouping of physical components, and modularity is the decomposition of a product into subassemblies and components. Components represent the basic physical units of modules. The function is what the product does. The function diagram formed in a product decomposition is called a function structure.
Architectural innovation (Henderson & Clark, 1990; Magnusson et al., 2003; Sköld & Karlsson, 2013)	'Architectural innovation is the reconfiguration of an established system to link together existing components in a new way. This does not mean that the components themselves are untouched by architectural innovation. The important point is that the core design concept behind each component – and the associated scientific and engineering knowledge – remain the same.' (Henderson & Clark, 1990, p. 12)	**Product architecture** **System architecting** (Forsberg, 1992; Tomiyama et al., 2007; Ulrich, 1995)	Product architecture is the way in which the functional elements of a product are arranged into physical units and how these units interact. System architecting is the process of transforming system-level specifications into component-level specifications. The system-wide decomposition of complex products or large engineering systems decomposes the design problem into smaller sub-problems that can be handled easily. In this study, system architecting is performed to identify modules and their interfaces and to show product architecture.

2.1 Modular innovation (management approach) and modularity (engineering approach)

Modular innovation has been defined in the management literature as improvements in individual components, while the overall design and the links between the design concepts remain the same (i.e., unchanged) (Henderson & Clark, 1990). This conception of modular innovation has been subsequently adopted in the innovation and technology management literature, where authors have focused on how modular innovation contrasts with architectural innovation (e.g., Chen & Liu, 2005; Chou et al., 2016; Magnusson et al., 2003). Primarily, this has been done to show how innovation takes place in isolated modules within the broader product design and to explore the implications and challenges of such innovation.

Indeed, in the management literature, modular innovation is seen to have particular challenges due to its insular nature. For instance, modular innovation may encounter technological misfits in the current product architecture (Clark & Fujimoto, 1991; Pil & Cohen, 2006). Therefore, it is argued that leaps in component technology may entail longer lead times (due to the need to achieve a proper fit of the new component into the existing architecture). Alternatively, the component may be shelved for future use or spun off into other applications. Researchers argue that these challenges is mostly because dominant architectural designs dictate the organizational structure of new product development, making it difficult for modular innovations to change existing architectures (Christensen, 1997; Hofman et al., 2016; Pil & Cohen, 2006;).

The engineering approach takes the physical features of the module within the broader design even further. According to the engineering literature, a *module* is a physical or conceptual grouping of physical components, while *modularity* is the concept of decomposing a system into independent parts or modules that can be treated as logical units (Pimmler & Eppinger, 1994). The application of modularity to designs results in modular product design to accommodate agile product development (Anderson, 1996). Modular product design refers to designing products, assemblies, and components that fulfil various functions through the combination of distinct building blocks or modules (Kusiak and Huang, 1996; Pahl and Beitz, 1996). Therefore, it could be said that the mainstream definitions of modular innovation and modularity are quite similar in both the management and engineering approaches.

2.2 Architectural innovation (management approach) and system architecting (engineering approach)

In the management literature, *architectural innovation* refers to the reconfiguration of an established system to link together existing components in a new way (Henderson & Clark, 1990:12; see also Magnusson et al., 2003; Sköld & Karlsson, 2013). Thus, conceptually, architectural innovation can create completely new interfaces between modules and components. Architectural innovation has been viewed in the innovation management literature as a way to create a system-level change as well as a change in markets and technologies (e.g., Abernathy & Clark, 1985; Christensen, 1992). More recently, research on architectural innovation has explained how firms are able to deal with strategic issues of dominant design using different roles, such as innovator and follower (Argyres et al., 2015; Park et al., 2018).

In the engineering literature, the focus is more detailed and based on explaining functionality and design. In this regard, *product architecture* is defined as the arrangement of physical components and their interaction (Ulrich & Eppinger, 2008). Thus, product architecture is defined as a scheme by which the *function* of a product is allocated to the physical components or structure of a product. The choice of product architecture has wider implications and is linked to the overall performance of the firm. Product architectures are associated with specific R&D issues including ease of product change, product variety, product performance, the division between internal and external development resources, and the way in which development is managed and organized (Albers et al., 2011; Baldwin & Clark, 2006; Boneema, 2011; Borches & Boneema, 2010; Fujita & Yoshida, 2004; Huang et al., 2007; Jiao & Tseng, 2000; Komoto & Tomiyama, 2012; Kusiak & Huang, 1996; Marion et al.; 2015; Martin & Ishii, 2002; Simpson et al., 2001; Sosa et al., 2003; Stone & Wood, 2000; Ulrich, 1995).

Furthermore, in order to comprehend product architecture, one must understand how system architecting—another key engineering concept—is performed. In this context, *system architecting* is the process of transforming system-level specifications into component-level specifications (Forsberg & Mooz, 1992; Tomiyama et al., 2007). System architecting is part of the conceptual design phase in which principle solutions, products' main functions, important sub-functions, modules, and their interactions are determined in order to achieve successful system design (Chmarra et al., 2008; Dieterle, 2005; Hehenberger, 2009; Pahl & Beitz, 1996; VDI 2206, 2004). The concepts used in the system architecting tasks are as follows: *a function*, which is what the product does in terms of its internal properties; *a core subsystem*, which is introduced in this study to identify those subsystems that represent main differences between the latest state of a product and previous versions; and *a module*, which is the physical composition of a product and its components, which represent the basic physical units of modules (see Table 1).

2.3 Interplay between modular and architectural innovation and their roles in technological radicalness

The concepts of modular and architectural innovation present technological explanations for how products are introduced through new modules in the core subsystems of a product (modular) and how the interfaces among these modules are made (architectural) (Henderson & Clark, 1990; Magnusson et al., 2003). Innovation in either of these types is made to improve the functions of products, leading to either incremental or radical innovation in the functions. Establishing this, however, leads to challenges and intense debate on radicalness and the nature of innovation. For instance, the Tesla electric car has been rejected as a 'disruptive innovation' due to its price tag and competitive entry (Bartman, 2015; Christensen, Raynor, & McDonald, 2015). It is also debatable whether it can be classified as a radical innovation *as a whole* given the performance metrics of some of the car's functions (e.g., mileage is poorer, yet acceleration is better) when compared to the internal combustion engine or the technology in hybrid cars. Nonetheless, there are significant advances at the module level of Tesla's cars, which may prove to greatly impact the market as the product family unfolds (Sköld & Karlsson, 2013). From a broader strategy perspective, looking closer at modular innovation is useful since it helps to shed light on the process which creates radically new product functionalities and ultimately customer value. However, this value could emerge regardless of whether the whole product is seen as 'radical' or 'disruptive'.

Regardless of the conceptual debates referred to above, it is clear that modular and architectural innovation are interdependent, and that this interplay may lead to different levels of technological radicalness in products' functions as well as customer value. These interdependencies and related solutions have already been identified in the classic literature on modular and architectural innovation. Most of this literature suggests various ways of fixing the integration issues of modular innovation, such as separating the organization of modular innovation activities (i.e., components representing the basic physical unit of a module) and conducting activities that try to push the current architecture away from the core activities of existing product structures (Christensen, 1997; Magnusson et al., 2003). As Christensen describes, '*if a redesign of a component impacts the performance of other components in a different way, engineers may not know with whom they need to work, what they need to know, when they need to know it, or how to solve new mutual problems when an innovation involves a significant change in product architecture and changes the inter-module interfaces significantly* (1997, p. 120)'. A key response would then be to align modular innovation, architectural innovation and managerial coordination. While several studies have focused on architectural innovation (see Chen & Liu, 2005; Henderson & Clark, 1990; Hofman et al., 2016; Tucker et al., 2015; Ulrich, 1995), the understanding of the value of modular innovation and its impact on product architectures, and subsequently product functions, is inadequate.

We argue that an individual module's new technological features and its product architecture may entail newness, presenting valuable functions that provide substantially better features and performance to satisfy existing or new customer needs, or even to draw customers away from other products (Chandy & Tellis, 2000; Füller & Matzler, 2007; O'Connor & Veryzer, 2001; Van den Hende & Schoormans, 2012). For existing customers, the introduction of a new technology in product modules can influence existing market technologies, as well as performance and value offerings to the customers who currently satisfy their needs through existing products with 'old modules.' From a technological product development viewpoint, our discussion thus concerns a 'technological ripple effect' potentially generated by modular innovation, which may start within a single function, product or firm.

The extant literature suggests different management mechanisms for modular, architectural and radical innovation platforms, whereby each platform is argued to be classified into having different organizational and resource requirements (Sköld & Karlsson, 2013). For module-driven technological innovation, we refer to changes in components that encompass new modules being introduced as part of R&D and manufacturing efforts. This comprises complex technologies and advancements in product families (Sköld & Karlsson, 2013). For very new technological modules, product classification and product platform consequences cannot be understood in a vacuum. We argue that modular and architectural innovation often takes place as part of a process, to the extent that new technological modules have a strong influence on existing product architectures. New modules may reshape existing architectures while also forming the basis for the generation of entirely new product architectures. This R&D-driven sequential process in technology modules and architectures fosters possibilities for radical innovation[1]. Figure 1 summarizes this logic, which will be further examined and illustrated in the empirical part of the study.

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[1] While we discuss and empirically study the process of module driven innovation in this paper, it should be acknowledged that it is also possible that modular and architectural innovation develop and are dealt with concurrently or in different types of progressions. Also, the new functions could be a factor of either 'technology push', where the module is identified before the functionality, or via 'market pull', where the functionality is determined first, leading to the design of modules that enable that functionality. We thank the anonymous reviewer who pointed these issues out.

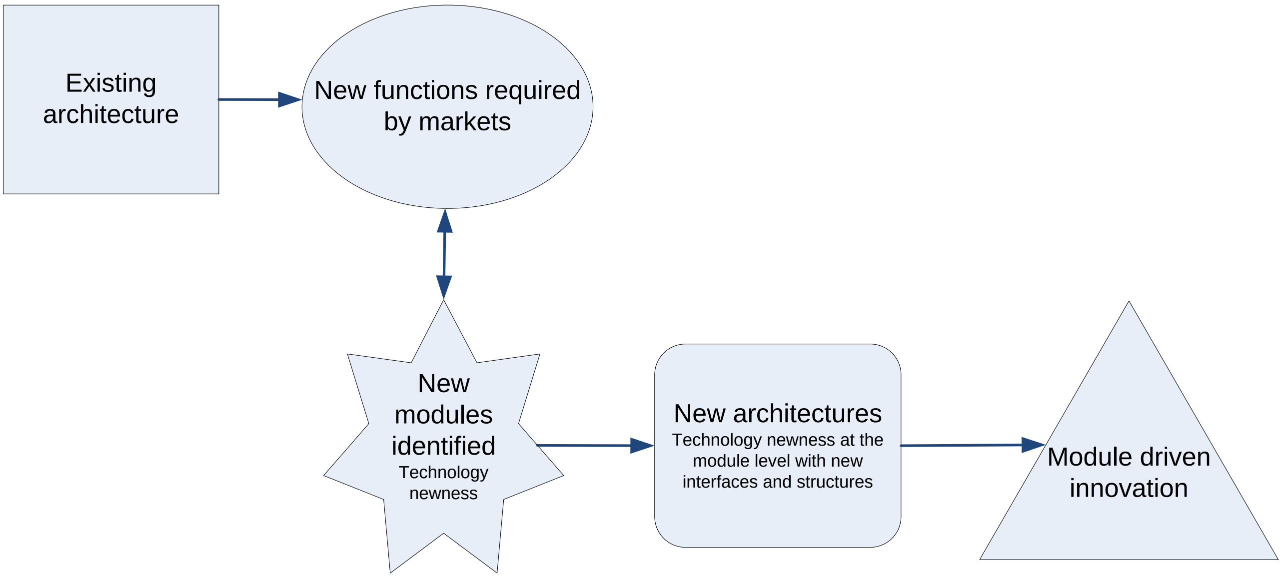

Figure 1. Module-driven technological innovation

3. Methodology

In this study, we discuss the phenomenon of modular innovation and its relation to architectural innovation (Henderson & Clark, 1990; Hofman et al., 2016; Magnusson et al., 2003; Sköld & Karlsson, 2013) and empirically examine two products using an engineering approach of system design. A system architecting approach (Habib, 2014; Komoto & Tomiyama 2012; Tomiyama et al., 2007; Ulrich,1995) is applied to perform the functional decomposition of the products and then map the product functions onto a physical structure, i.e., modules and subassemblies. Subsequently, the product architecture (Jiao & Tseng, 2000; Pimmler & Eppinger, 1994; Ulrich & Eppinger, 2008) is developed from modules with realizable interfaces. The purpose of this analysis is to, first, demonstrate the core modules of the product, second, determine the linkages and interfaces between modules, and third, demonstrate how new functions are spurred by the introduction of new technology into the module(s) of a product (which is a key determinant for product novelty).

Our study examines the system design of two products: electric cars (Tesla Model X) and autonomous vacuum cleaning robots (Roomba from iRobot). Both examples represent new-to-the-world performance features manifested by their functionalities (a vacuum cleaner that cleans by itself and a fully electric SUV with superior range). We selected the two products based on the assumption that we would be able to demonstrate how changes in modules and components could affect the architecture, leading to radically new product functions. More broadly, the analysis will be helpful in bridging the gap between the engineering and management approaches, and in so doing, will demonstrate the interplay between modular and architectural innovation.

We describe the architectures of these products. Then, we pinpoint the modules in which new technology has been implemented and break down the new technologies through the examination of patent data attributed to the different modules of the respective products. Patents describe the features of the new module-technologies that were imparted and enable us to present a discussion of why technological innovativeness is rooted at the module level and how module-level technological innovation affects product architectures. This analysis informs us on the resulting outcome of the different levels of radical technology innovation.

In conducting the analysis using system architecting (Komoto and Tomiyama 2012; Tomiyama et al., 2007), we investigate how novel outcomes derived from the technological newness at a product module level have led to changes in product architectures (i.e., interfaces and structure), eventually resulting in technologically radical product innovation. We follow a two-step analysis process to examine and validate these findings. In the analysis of the first example, we compare a manual vacuum cleaner (VC) with the autonomous vacuum cleaner (AVC) Roomba introduced by iRobot. The comparative analysis helps us to pinpoint the new technologies in the modules and components as well as new functions and their effect on product architecture (see, Table 2 and Table 3). In the second example, we examine the Tesla Model X and compare it to an internal combustion (IC) engine car and a hybrid car. The comparative analysis of all three car types helps us pinpoint the new technologies in the electric car components, impart new functionalities, and better understand how this technology changes the product architecture (see Table 4 and Table 5).

3.1 Data collection and analysis

We examined these two products sequentially. First, the autonomous Roomba was examined from product manuals, product videos and patent data provided by iRobot. Emphasis was placed on noting the new technology used in its modules and the resulting functions and effects on product architecture. Second, Tesla's electric car was examined from product manuals, videos and patent data provided by Tesla Motors Inc. This initial research helped us to identify the evolution of both products. The data collected (Table 2 and Table 4) was used in the analysis and synthesis of the two products (Joergensen, 2000). We analysed the two products using a hierarchical decomposition to facilitate the physical realization of the system in the form of modules and their interfaces (Ericsson & Erixson, 1999; Pahl & Beitz, 1996). Then, we performed a synthesis of the two products for the development of a system architecture (Habib, 2014; Jiao & Tseng, 2000; Ulrich, 1995; Ulrich & Eppinger, 2008). There are several advantages to this approach. First, it allows us to demonstrate how complexity is managed through the hierarchical decomposition of the system and the development of modules and their interfaces. Second, we are able to identify newness in technology that imparts new functions in relation to customer requirements. This process helps managers to innovate their products early in the system design phases. Finally, we are able to demonstrate the potential for redesigning and developing multiple system architectures have in facilitating next-generation products based on radical technology innovation.

In conducting the analysis, we stressed the understanding of two dynamics: first, product functionalities and technological changes at the module level that made the products radically/incrementally innovative from a technological perspective, and second, how technological changes at the module level affect the products' architectures (i.e., interfaces) and structures.

3.2 Patent data sources

The data on the iRobot Roomba and the Tesla Model X were collected from the following sources:

a. iRobot.com patents, 2015
b. Freshpatents.com, 2015; iRobot corporation patents
c. Freshpatents.com, 2015; Tesla Motors Inc. patents
d. Patentencyclopedia.com, 2015; Tesla Motors Inc. patent applications

We verified the patent data of the products against the official data indexes of the published patents. Details of the patents are in summary Tables A1 and A2.

For the autonomous vacuum cleaner, we investigated all patents related to the iRobot® Roomba® 600 series. A total of 56 patents were examined, which were time stamped from 2003 to 2014. Out of these 56 patents, 19 are documented in this study as being related to core modules that represent new technologies and/or modifications and improvements to existing technologies. The remaining patents are not documented in the study as they are the early versions of existing patents, and do not provide additional insight into describing novelty in the core modules.

For Tesla's electric car, we aggregated all patents made publicly available between May 2009 and September 2015, when Tesla's Model X was launched. Thus, we have included all the patents up until the launch of the Tesla's Model X. We did not investigate any patent data registered after this date.

The search yielded a total of 331 patents. Out of these 331 patents, 101 are documented in this study as being related to core modules containing new technologies and/or modifications and improvements to existing technologies. Of these 101 patents involving technological changes, 60% are related to the battery pack. The remaining patents are not documented as they are not directly related to core technologies and some of them are earlier versions of existing ones.

3.3 Data coding

We extracted data and information following the four methods mentioned below, and we coded the patent information based on the following coding themes drawn from the research question of our study. The coding themes were as follows: What is the technological newness?; Which modules and components contain new technology?; What new functionalities are introduced due to new technologies in the modules?; and, How do the new technologies in the modules affect the architecture of the product? Based on these data codes, we developed summary tables for the patents (Table A1 and Table A2) from which we drew the figures on system architecting (Figure 2 and Figure 5) and system architecture (Figure 3 and Figure 6). The data collection process (i.e., the four methods) and the delineation of the different layers of the coding process include the following:

a. An analysis of the case examples (i.e., from manual to autonomous vacuum cleaner and from conventional IC car to electric car) based on physical observation, product videos and product manuals. This was useful to identify the fundamental differences in the systems being studied (See Table 2 and Table 4).

b. The collection of patent data on different modules and components that indicates technological newness. This was then placed in coding tables, including application number and the description of the patents (See Table A1 and Table A2).

c. The application of the coding data on technological newness and the specific module to implement the system architecting approach in order to perform the functional decomposition of the product and the mapping of these functions into modules and subassemblies as prescribed in the literature (See Komoto and Tomiyama, 2012; Tomiyama et al., 2007). This step identifies the functions and modules that differ from conventional products in the same product category.

d. The development of the product architecture from the new modules with realizable interfaces following the methods used in other studies (See, Jiao & Tseng, 2000; Pimmler & Eppinger, 1994; Ulrich & Eppinger, 2008). These architectures represent the newness in the technology of the module and their interaction.

4. Study 1: Roomba iRobot autonomous vacuum cleaner

In functional terms, a vacuum cleaner is a device that sucks dust and dirt from floors by creating a partial vacuum through a suction system. With the passage of time, new technologies and functionalities have been added to the system according to customer requirements. The new technologies give added functionality in sensing and self-navigation to generate and support motion. New technology such as sensors, actuators, a control system and a suction system have been introduced to the manual system. Thus, manual vacuum cleaners can be upgraded to autonomous vacuum cleaners, giving them added functionality. Our initial analysis demonstrates the fundamental differences in manual and autonomous vacuum cleaning systems, as shown in Table 2.

Table 2. *Commonalities and differences in the function and module levels of manual vacuum cleaners and autonomous vacuum cleaners*

Functional Level		**Module and Components**	**Manual Vacuum Cleaners**	**Autonomous Vacuum Cleaners**
Functions	Sub-functions			
To sense	*To sense dust*	Optical sensor		X
	To sense debris	Debris sensor		X
	To follow walls	Proximity sensor		X
	To avoid height	Cliff sensors (optical)		X
	To sense obstacles	Bumpers and mechanical switches		X
To self-navigate	*Room coverage*	Navigation and behaviour system (i.e., control system)		X
	To stay within a particular area	IR receiver, virtual light house, microcontroller		X
To collect dust and debris	*To sweep dust*	Main brush module, side brush module		X
	To suck and lift dust	Suction module	X	X
To support and generate motion	*To support*	Chassis	X	X
	To move	Drive system—drive wheels	X	X
		Wheel actuator		X
		Shaft encoder		X
	To generate power	Battery module	X	X
To store dust and debris		Bag module (dustbin)	X	X

Note: The shaded areas represent the newness in the AVC robot at the module level. Components represent the basic physical units of modules (Refer to Table 1).

Autonomous vacuum cleaning robots normally navigate within a living space to vacuum floors. These robots automatically guide themselves and clean surfaces by using sensors to avoid obstacles, such as walls, stairs and furniture. We analysed an AVC robot to identify its main components and the interfaces between them as well as to understand the architecture of the system. This analysis was then utilized in a hierarchical decomposition of the system to identify its core system modules.

4.1 Using hierarchical decomposition to identify core modules in AVC robot architecture

A hierarchical product decomposition was conducted as proposed by Ulrich (1995). The decomposition of the AVC robot is represented in the function-subsystem-module domains, as shown in Figure 2. In this decomposition, the primary function of the robot is to clean floors. Initially, the functional decomposition reveals that the main functions of an AVC robot are: a) to sense (the environment), b) to collect dust and debris, c) to navigate by itself, and d) to support and generate motion.

These functions are then linked to core subsystems (e.g., the sensor, cleaning, navigation and behaviour control, body, and drive systems). These subsystems provide information about the technical solutions in the form of modules. For instance, in the cleaning system, the suction module, the main brush module and the side brush module are identified as technical solutions. Each module can be further decomposed into components, which are not shown in this model.

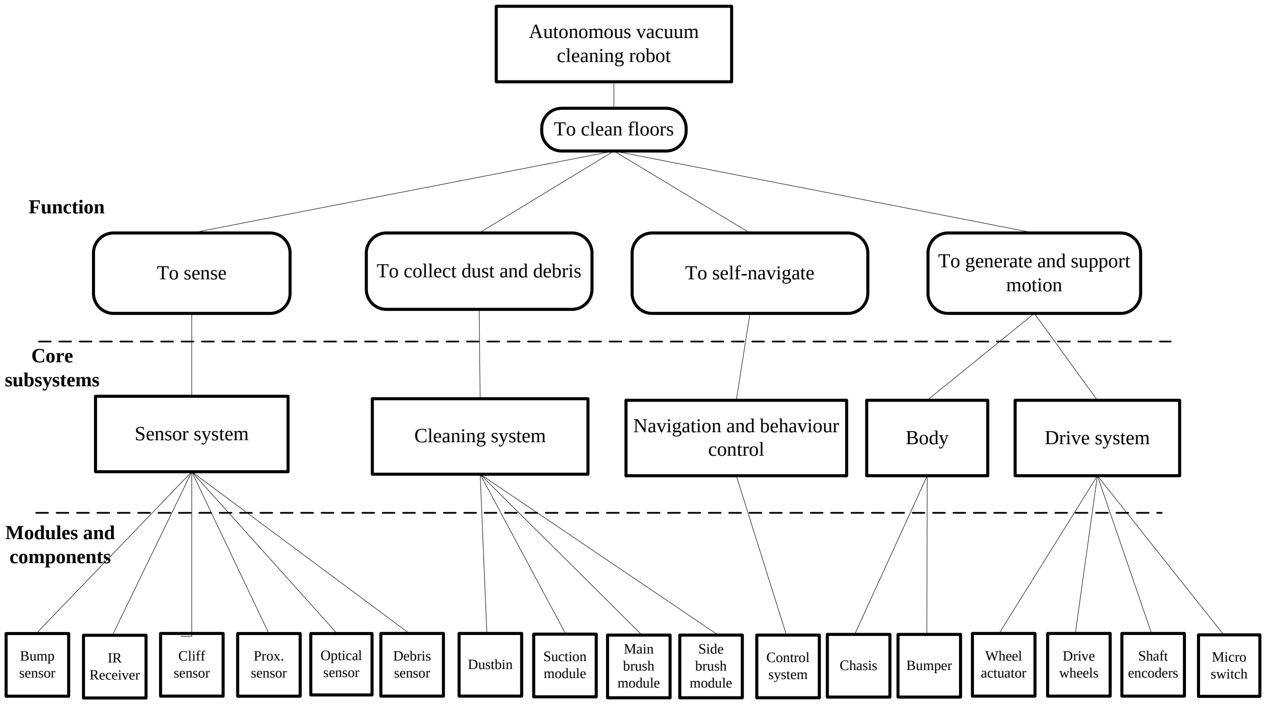

Figure 2. Decomposition of the autonomous vacuum cleaner into its function and physical structure.

The patent data on the AVC robot reveal that modifications and new technologies have been introduced into subsystems related to navigation and behaviour control, the sensing system, and the cleaning system. These patents (Table A1 in Appendix) exist mainly in the subsystem of navigation and behaviour control, the vacuum brush assembly, the bumper assembly and the sensor system. A visual depiction of the architecture of the modules in the AVC robot is shown in Figure 3. In the figure, the modules and components represent newness in technology. The interfaces (flows) between the components are shown with arrows in the figure. *Interfaces*, as such, are one of the main aspects of product architecture and our empirical examination demonstrates that technological changes in core modules have affected or changed the interfaces of product architecture. These interfaces highlight the broader interplay between modular and architectural innovation, as discussed in the following section.

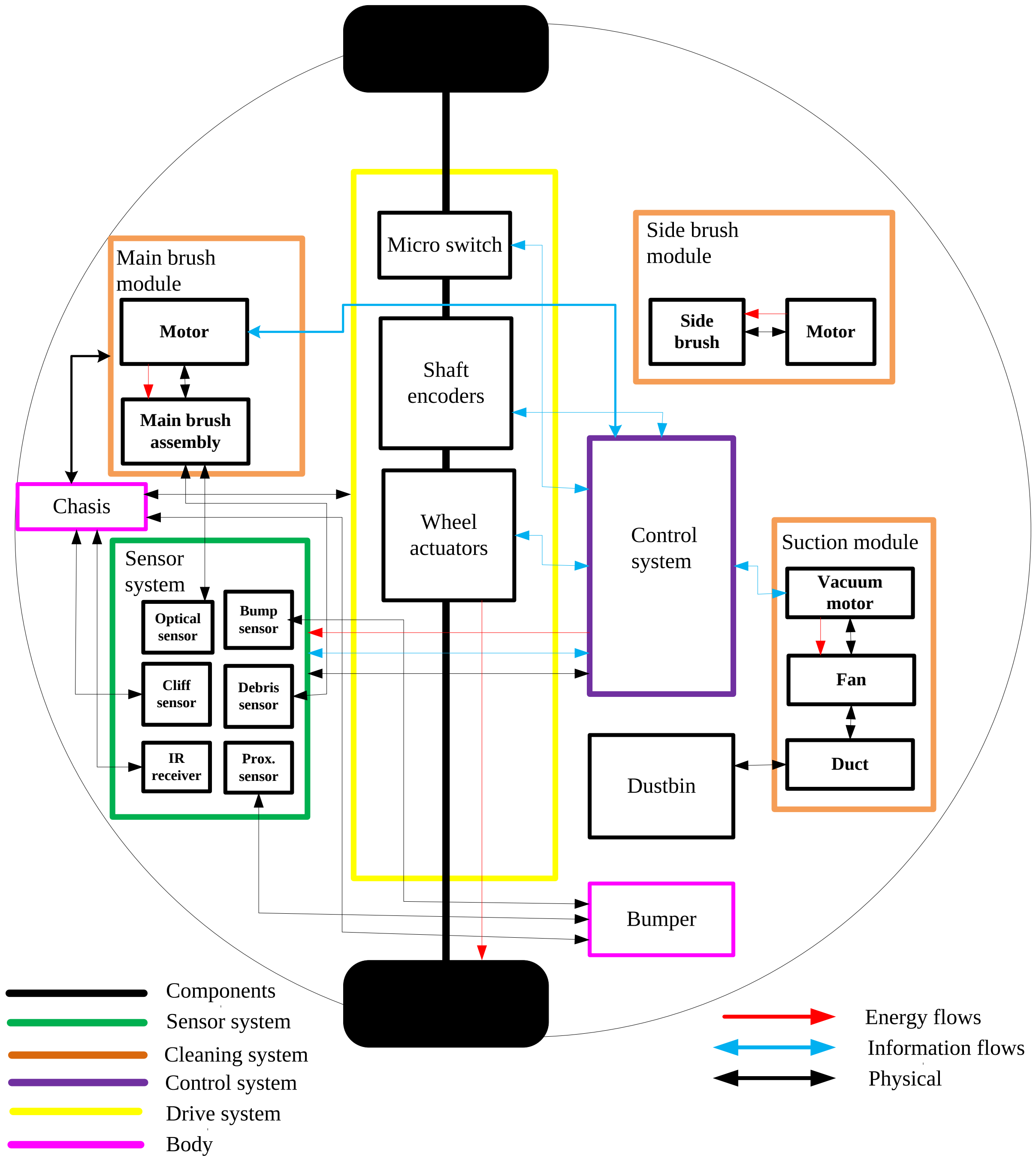

Figure 3. Architecture of the autonomous vacuum cleaning robot.

4.2 Technological newness at the modular level that changes the architecture

Throughout the entire data set, we have delineated the structure of the AVC robot in order to identify the commonalities and differences at the functional and physical levels compared to manual VCs (see Table 2). The AVC robot adds new functionalities, such as *self-navigating* and *sensing the environment*, to manual systems. In order to achieve these functionalities, new modules, including sensors, microcontrollers and a virtual lighthouse, have been added to the systems. However, other systems and components, such as batteries, chasses, suction systems, and storage bags, are common in both autonomous and conventional VC systems.

Technological newness in iRobot is evident from the patent data (see Appendix A1), which supports the progression of these events. The dates of the navigation and behaviour control system patent publications range from 07/22/2003 to 04/09/2013. From the patent data, it can be observed that during this time, R&D from iRobot incorporated various improvements into the control and navigation system. These improvements are related to detection, robot confinement, multi-mode coverage for autonomous robots, sensor integration, robot navigation etc. The R&D process in the sensor system was an ongoing process to improve navigation and detection in the system. The publication of the sensor system patents were published between 10/18/2005 and 09/11/2014. During this time, multiple sensors such as proximity, bump, cliff, IR receiver and debris sensors were inserted into the architecture of autonomous robot to aid in the detection and navigation systems. These new sensors are able to navigate along walls and sense height, obstacles, and dust and debris. These technological developments impact the architecture of the system as well.

Changes in product modules and architecture do not happen in isolation; rather, our case study demonstrates that changes in product modules enable a sequential novelty, which flows from module towards architecture and then finally lead to radical new functions. As our analysis demonstrates, in the case of the AVC robot, the addition of new modules not only introduced new technology, but also subsequently altered the vacuum cleaner architecture in two ways: a) through new interfaces between modules and b) through changes to the physical structure (i.e., from manual to autonomous function).

4.3 Changes in the architecture with new interfaces

The Roomba robot data shows that new modules and components, such as sensors (bump, cliff, debris, proximity etc.), control systems, drive systems and main side brush modules, introduced in autonomous robots differ from the modules in manual vacuum cleaners. The architecture of the AVC robot (Figure 3) shows that the newness in technology introduced through these modules fosters new kinds of interfaces that change the system architecture. For instance, the interfaces between the control system and the sensor system include energy flows, information flows, and physical or geometrical connections. Thus, these new modules have altered the system architecture and introduced added functionality (Table 3).

Table 3. Technological newness in new modules resulting in functional improvements and impacting the architecture to produce new interfaces

New module and components (technology newness)	Interface with	New interfaces	New function
Navigation and behaviour control system	Sensor system, wheel actuators, shaft encoders, and suction module	Physical interface and information interfaces	Able to self-navigate
Sensor system - Optical sensor - Acoustic sensor - Proximity sensors - Cliff sensors - Mechanical switches	Control system, main body, bumper, main brush etc.	Physical interface and information interfaces	Able to sense and navigate - Debris - Dust - Walls - Height - Obstacles
Drive system - Wheel actuator - Shaft encoders - Micro switches	Control system, wheels and body	Physical interface, energy and information flow	Able to generate motion
Main brush and side brush module	Bumper and main body	Physical interfaces	Able to sweep and collect dust and debris
Suction module - Vacuum motor - Fan - Duct	Control system, dustbin, body etc.	Physical and information flows	Able to suck and lift dust and debris
Bumper assembly	Body, bumper sensor, and proximity sensor	Physical interface	Able to assist in sensing obstacles to navigate in living spaces

In short, based on the investigation of the AVC robot, technological newness in the modules has been found to introduce new functionalities that are primarily related to control and navigation, as well as to autonomous functions such as being self-charging, self-cleaning, and having the ability to detect dust and debris. These radical changes represent the main differences between the AVC robot and manual vacuum cleaners.

5. Study 2: Tesla’s Model X

The trend towards designing and building fuel-efficient and low-emission vehicles has increased greatly over the last decade driven by concerns over environmental issues and depleting fuel resources (Chen, 2010). At the forefront of this trend has been the development of hybrid vehicles that combine relatively efficient combustion engines with electric drive motors. Currently, most common hybrids utilize a parallel drive system although the implementation of this system varies across car manufacturers (Chan et al., 2010; Jones, 2005; Rawlinson et al., 2012).

The differences in the basic architectures of hybrid electric vehicles (HEVs), internal combustion engines (ICEs) and battery-powered electric vehicles (BEVs) are presented in Table 4. In general, hybrids provide improved fuel efficiency and lower emissions than internal combustion engines. However, hybrid cars have very complex and expensive drive systems due to the use of two different drive technologies, i.e., an electric drive system and an internal combustion system. In addition, hybrids still depend on ICEs for a portion of their power, and the inherent limitations of these engines prevent hybrid vehicles from achieving the desired levels of pollution emission control and fuel efficiency. Therefore, several car manufacturers, including Tesla Motors, are researching and utilizing all-electric drive systems. The basic architecture of a BEV is shown in Figure 4, where EM= electric machine, Trans= transmission, VSI= voltage source inverter, and BAT=battery.

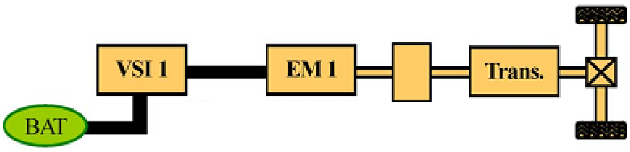

Figure 4. Architecture of a battery-powered electric vehicle (adopted from Chan et al., 2010).

The characteristics of and differences among the three architectures (ICE, HEV, BEV) are shown in Table 4.

Table 4. Characteristics of and fundamental differences among ICEs, HEVs and BEVs

Denominator	**ICE**	**HEV**	**BEV**
Propulsion	Internal combustion engine	• Electric motor drives • Internal combustion engine	Electric motor drives
Energy storage subsystem (ESS)	Fossil fuels	• Battery • Supercapacitor • Fossil fuels or alternative fuels	• Battery • Supercapacitor
Thermal management subsystem	Coolant jackets around engines	Cooling system for engine battery and electric motor drive	Cooling system for engine battery and electric motor drive
Energy conversion	Chemical to mechanical	• Chemical to mechanical • Electrical to mechanical	Electrical to mechanical

5.1 Using hierarchical decomposition to identify modules in Tesla's Model X architecture

The Tesla Model X is a BEV developed by Tesla Motors Inc. Tesla Motors' R&D focuses primarily on the areas of propulsion, energy storage and temperature regulation. In this study, in the decomposition of Tesla's electric car, we have identified the main functions of the product and then selected the technical solutions of the core system. The primary difference between a conventional car and an electric car are the core systems, as described in Table 4. In this analysis, the core systems are further decomposed to identify the modules that represent the newness in technology and the main architectural differences between conventional cars. Tesla’s patent data support this system architecture overview.

The hierarchical decomposition of the core systems of the Tesla Model X is represented in function-subsystem-module domains, as shown in Figure 5. In this decomposition, the primary focus is on the main functionalities of an electric car. The functionalities are then decomposed into four sub-functions: a) to provide energy, b) to propel the car, c) to control the temperature and d) to control the subsystems.

These functions are then linked to core subsystems including the energy provision and storage system (ESS), electric propulsion system, vehicle thermal management system, and main control system. These subsystems are further decomposed into modules and components. For instance, in the electric propulsion subsystem, the motor, the inverter and the gearbox are the main modules. Each module is further decomposed into components and parts that are not shown in this model, yet are included in the patent data. Here, data on the newness of the components in each subsystem are provided (see Figure 5). In the figure, the main functions are connected to the core subsystems. These subsystems are further decomposed into modules and components.

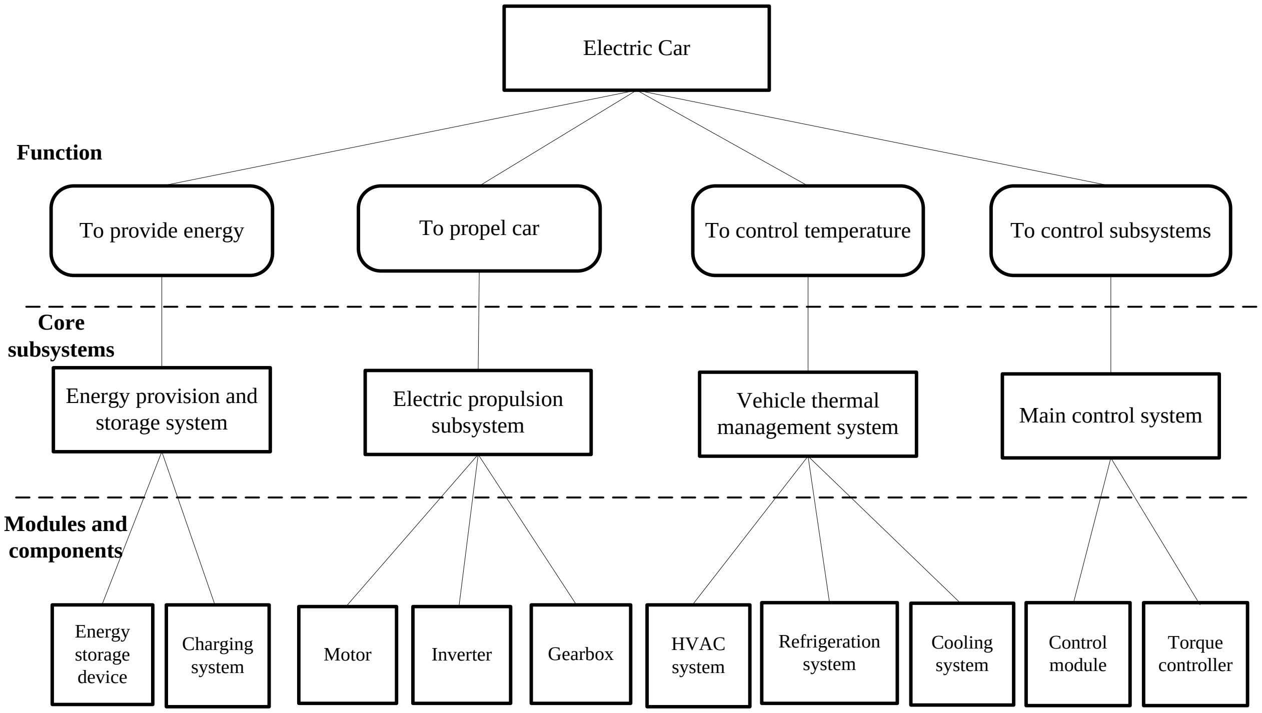

Figure 5. Decomposition of the core system of the Tesla electric car into function and physical structure.

The patent data of Tesla Motors show that new technologies have been introduced primarily in the subsystems related to energy storage, electric propulsion, temperature regulation and the control system (see Figure 5 and Table A2).

In the Tesla car architecture, seven modules have been identified (Figure 5) as being the main functional elements in the electric vehicle (EV) that differ from elements in conventional cars. The generic architecture of the Tesla car (Figure 6) is primarily developed from the following four subsystems.

1. (Electric propulsion subsystem) An integrated drive system assembly combines an electric motor, a power inverter assembly and a gearbox into a single, multi-piece enclosure.
2. (Vehicle thermal management system) A vehicle thermal management system comprises an HVAC, refrigeration and cooling system for cooling energy sources and motor systems.
3. (Energy provision and storage system) An energy storage and provision system are made up of a battery pack and charging system. Both are connected to the control module and the inverter for propulsion.
4. (Main control system) A system that controls all of the above systems.

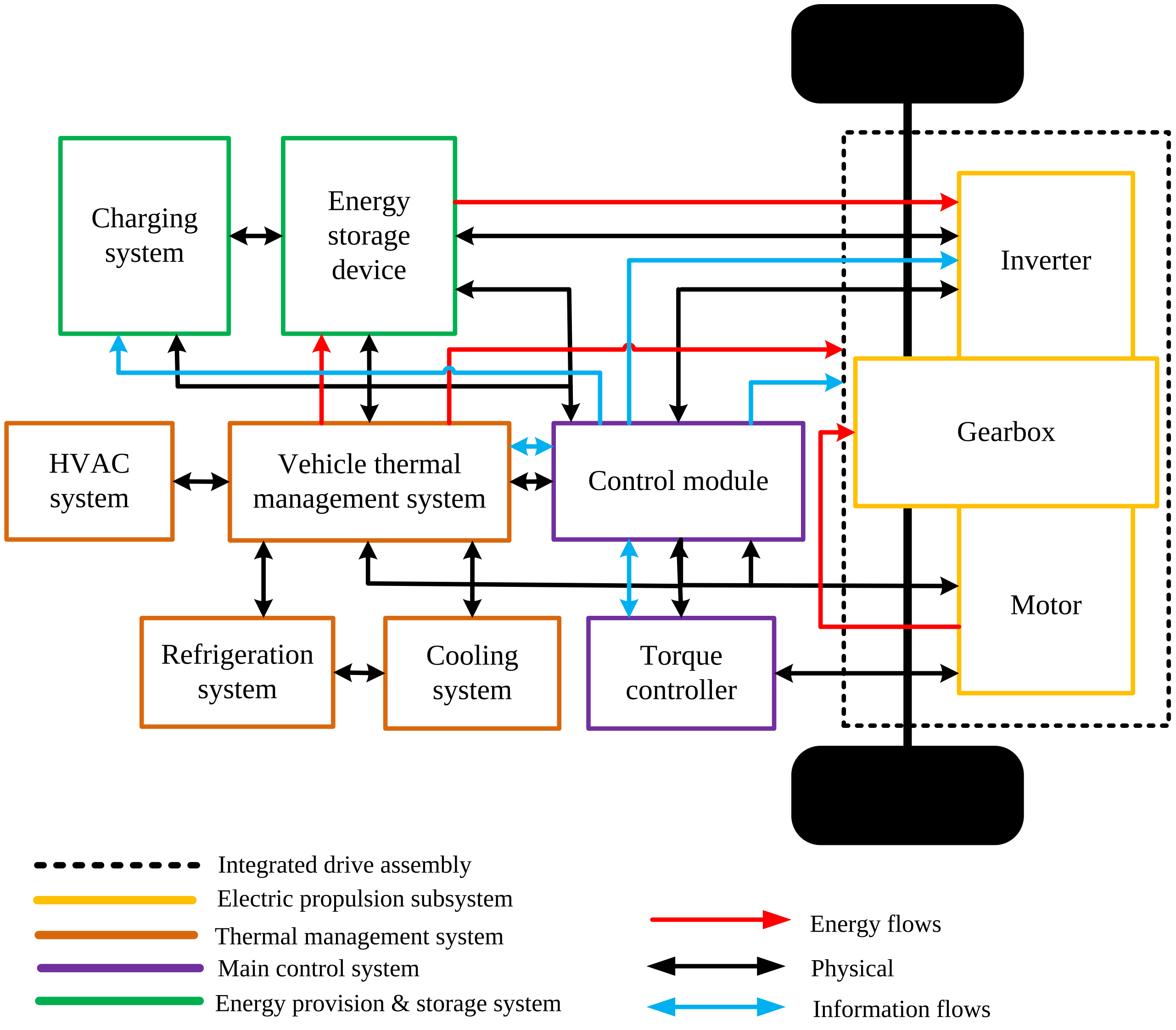

Figure 6. Architecture of Tesla's electric car.
Note: Modules in the main subsystems are illustrated through the use of coloured lines.

5.2 Technology newness at the modular level changes the architecture

The patent data show that the potential radical outcomes in Tesla's electric car exist primarily in the areas of propulsion, energy storage and temperature regulation. The above-listed developments not only improve functionality, but they also alter the architecture at the module level. For instance, in the propulsion system, the introduction of new technologies in modules such as the controllers and the sensors results in improved torque performance and a better information flow interface.

Similarly to the previous case, technological newness in Tesla model X is evident from the patent data (see Appendix A2), where we also find data that support the progression of these events. The publication of the motor assembly module patents were between 05/14/09 and 05/07/15. From the patent data, it can be observed that during this time Tesla's R&D process brought about various improvements in the control and drive assembly system. These improvements were primarily related to torque and flux distribution, which improved efficiency, the propulsion system, high-speed power and better integration with cooling system. The dates of the thermal management system publications ranged from 04/29/10 to 03/28/13. From the patent data, it can be observed that during this time Tesla's R&D process introduced new technology that brought about various improvements such as cooling to various systems, reduces complexity and improves system efficiency and safety.

The introduction of new technologies at the module level plays a crucial role in improving the safety, reliability and functionality of the car. New technologies in the energy storage and battery pack modules bring about several radical outcomes. First, functional improvements to the battery are achieved through the introduction of new technologies and systems improvements. For instance, new technologies, such as optical fibres, are used to monitor such issues as thermal runaways. Similarly, an overcharge protection device (OPD) is used to protect battery packs from the occurrence of potentially damaging overcharging episodes.

Second, battery safety is improved via technological developments like thermal barrier elements, which are used to prevent thermal runaways from propagating to other cells. Similarly, a battery pack gas exhaust system is used to minimize the effects of thermal runaways within a battery pack.

Third, newness in technology provides an improved protection system, enhanced system reliability and improved design. For instance, in a battery pack integration system, in which one insulating layer is interposed between the battery pack enclosure and the passenger cabin floor panel to achieve noise isolation, thermal isolation, and vibration damping. Here, the design and reliability improvements include a battery mounting structure that prevents condensation-induced corrosion from occurring between the battery terminals.

These technological developments impact the architecture of the system as well. The addition of new modules has not only introduced new technology and functionality in the system; it has also subsequently altered the Tesla car architecture through new interfaces between modules. Table 4 shows the main architectural differences between ICE cars and electric cars while Figure 6 illustrates changes in the product architecture with new interfaces (i.e., the interfaces between the modules) to represent architectural innovation.

5.3 Changes in the architecture with new interfaces

Tesla utilizes the technology in modules for architectural changes. For instance, one of the main architectural differences between Tesla Motors' cars and other electric cars is Tesla's use of an integrated drive assembly. Tesla car models use an integrated drive system assembly that combines such modules as the electric motor, the power inverter assembly and the gearbox into a single multi-piece enclosure. Combining these modules into a single enclosure has some advantages, such as reducing drive system complexity, reducing weight and simplifying the integration of the drive assembly of the electric vehicle. Moreover, these modifications reduce manufacturing costs and allow the flexible and lengthy electrical cables between the power inverter and the electric motor in a conventional electric vehicle to be replaced by short, low-loss busbars. Additionally, these changes simplify component cooling through the use of a common thermal management system, which includes a liquid coolant loop that is thermally coupled to the electric motor, the power inverter assembly and the gearbox.

The following examples in Table 5 illustrate details of a) technological newness at the modular level that provides functional improvements that represent modular innovation and b) changes in the product architecture with new interfaces (i.e., the interfaces between the modules) to represent architectural innovation. As in the case of Roomba, these changes also demonstrate the interplay between modules and architecture and thus have broader implications for the interplay between modular and architectural innovations as well as technological radicalness.

Table 5. Technological newness in new modules resulting in functional improvements and impacting the architecture to produce new interfaces.

New module (technology newness)	**Interface with**	**New interfaces**	**New function**
Refrigeration system, cooling system modules	Integrated assembly, control system, energy storage and charging system	Information flow, energy flow and physical interfaces	Provides cooling, reduces complexity and improves system efficiency and safety
Main control system comprising torque controller module	Drive motors, ESS, thermal management system	Information flows	Better control of all systems and improved torque performance
Motor module	Gearbox, main control system, torque control, thermal management system and inverter	Energy flow and physical interface and information interfaces	Provides propulsion, power and torque system
Inverter module	Motor, gearbox, control system and energy storage	Physical, energy flow and information flows	Improves control voltages
Charging system module	Control module and energy storage system	Information flows and energy flows	Optimizes charging through improved efficiency and protection
Energy storage device	Main control system, thermal management system, inverter and charging system	Energy flow and physical interface as well as information interfaces	Stores energy and charges, improves battery life, and reduces damage during charging

In short, researching the Tesla electric car shows that the technological newness in the modules introduces new functionalities primarily related to propulsion, energy storage and temperature regulation. These functions support a cleaner environment and improve performance due to electric energy through improved charging, cooling, torque and control systems. Ultimately, new technologies improve the safety, reliability and functionality of the electric car. Other recent developments, such as semi-autonomous functionality, have also been introduced in some Tesla models. These functionalities are the main differences between Tesla vehicles and conventional ICE cars. The new technologies they have produced alter the product architecture through new interfaces primarily related to energy and information flows.

6. Discussion and implications

Our study combines management and engineering approaches to modular and architectural innovation. It thus adds to the innovation and management literature, which tends to conceive modular and architectural innovation as distinct and separate ways to innovate in product design (e.g., Chen & Liu, 2005; Chou et al., 2016; Magnusson et al., 2003), and it is in line with the seminal work of Henderson and Clark (1990). However, following research which suggests a more interdependent approach between modular and architectural innovation (e.g., Carayannopoulos, 2009), we show that separating the two innovation types is not necessarily the best way to analyse new product development and innovation.

Using the patent data, manuals and system architecting, our study explains the evolution of the design of two products: iRobot’s autonomous vacuum cleaner by Roomba and Tesla’s Model X electric car. We identify the core design modules that evolve from manual to autonomous modules in Roomba, and the modules that evolve into a fully electric design in the Tesla car. Both examples demonstrate that modular innovation can lead to radical technology innovation in products, depending on the novelty introduced in the module. If the technology in the module/component is merely an updated version compared to the previous one, modular innovation is likely to influence incremental product innovation. On the other hand, if the new module is radically new, it demands new types of flows and interfaces between the components, effectively changing the overall product architecture. In fact, modular innovation can impact design (i.e., front-end issues), including how a product looks, the product architecture, and the production process, as well as the global production network (i.e., back-end issues) that is comprised by sourcing, R&D management, assembly, customization, and the integration of corporate and functional strategies into the firm’s innovation system.

Therefore, as our analysis demonstrates, there is a fundamental interconnection between modular and architectural innovation which can be discovered by taking a closer look at the actual engineering of the product architecture. In particular, our findings illustrate that technological newness at the module level, particularly spurred by new core components in the modules, can lead to radical technology innovation. Based on this, we argue that the degree of technological newness at the component level determines the extent to which modular innovation affects architectural innovation vis-à-vis radical/incremental innovation. This is because the technological newness in the module affects the design and architecture of the entire product (i.e., the interfaces and structure) as well as the performance and features. Again, integrating the management and engineering approaches is useful in understanding the interfaces through which changes in modules lead to architectural change.

Our study also contributes to the understanding of radicalness of product innovation. An array of authors have described incremental and radical innovation to be understood as two theoretical ends of an innovation continuum. In this respect, authors have given multiple explanations as to what constitute the axis of such continuum, including newness of technology and market, (e.g., Chandy & Tellis, 2000; Garcia & Calantone, 2002; Lynn & Akgün, 2001; Veryzer, 1998), business model change (Chesbrough & Rosenbloom, 2002), performance/output (Laursen & Salter, 2006), level of uncertainty (Dow & Werlang, 1992), degree of new firm knowledge (Dewar & Dutton, 1986), degree of new user knowledge (Markides, 2006) and time horizon for development and market adaptation (O’Connor et al., 2008). However, after examining a large body of literature, most contributions describing the difference between incremental and radical innovation are related to changes in technology and market, both from a micro- and macro perspective (Santonen et al., 2016; Garcia and Calantone, 2002). In the current research, the point of departure is taken from the firm perspective, more specifically the product perspective of technological newness in modules and their interfaces. We describe how technological newness in modules and interfaces bring about new, technical product functions that may be of value to existing markets, or develop new markets. Where our unit of analysis in this study is technological newness, we thus also bridge this to a market perspective, where, even though interlinked, the latter is not a focal point of this article. The following sections discuss in greater detail the implications of these results for research as well as practice.

6.1. Research implications: Revisiting modular and architectural innovation as a driver of radical technology innovation

Our conceptualization of modular innovation (see Figure 7) sheds new light on the mechanism of modular innovation and its connection with architectural innovation from a technology perspective. It shows how modular and architectural innovation, in sequence, affect the development of new product functionalities and radical technology innovation. We argue that this conception improves the understanding of the technological newness at the micro-level of product development.

In particular, we argue that modular innovation can help to determine the extent to which product innovation will follow a incremental or radical product innovation trajectory, especially when the interfaces between modular and architectural innovation are taken into account. The analytical framework, illustrated in Figure 7, highlights modular innovation and its resulting outcomes in product architecture, which can ultimately lead to different levels of technological radicalness in product innovation.

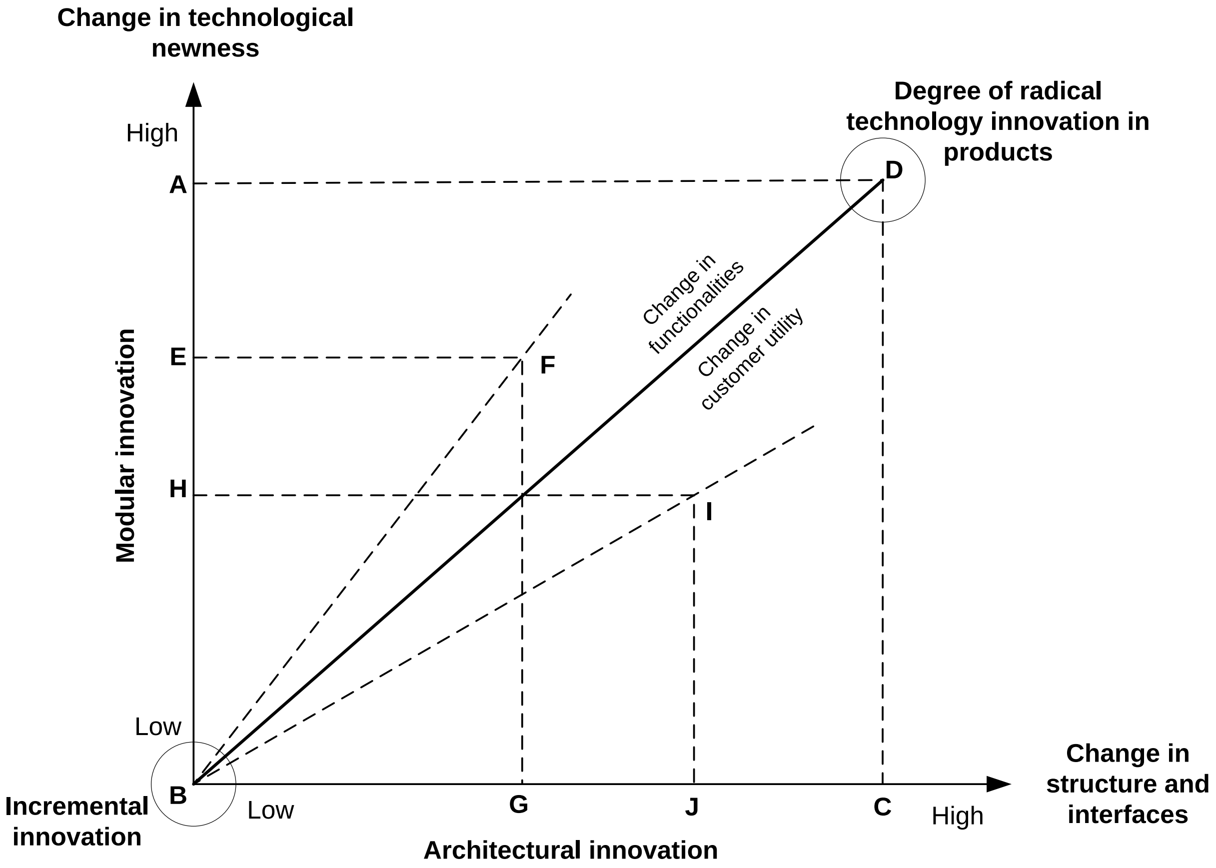

Figure 7. Explanatory framework for understanding how modular innovation affects architecture, leading to different levels of technological innovation in products.

In Figure 7, the vertical axis indicates the ‘degree’ of modular innovation in terms of technological newness, while the horizontal axis indicates the ‘degree’ of the architectural innovation, i.e., changes in architecture. Both axes illustrate high and low levels (degrees) of changes in the core parameters. The degree of change in modules normally includes performance outcome, size, weight and configuration complexity. A core parameter in modular innovation is the degree of change in terms of technological newness at the module component level. To demonstrate architectural innovation, Figure 7 indicates the degree of change in the interfaces between modules and components as well as in the product structure. These changes in modular innovation and architectural innovation lead to changes in product functionality, which in marketing refers to consumer utility. Changes in functionality, therefore, determine whether—or to what extent—a product will be incrementally or radically innovative as a product (see the two sides of continuum BD in Figure 7). This is aligned with the management approach in that the degree of innovativeness typically refers to the function and the experienced utility of a product, which results in combinational changes in product modules and product architectures.

The intersection line BD indicates the degree of radical innovation from a technological newness perspective, which is caused by changes in technological newness in the modular innovation (i.e., point A) and the architectural innovation (i.e., point C). Figure 7 illustrates a hypothetical scenario in order to explain the mechanisms of modular innovation and its resulting effects on other types of innovation.

Scenario ADC shows a hypothetical ideal point of highly radical technology innovation in a product, while *scenario HBG* shows another hypothetical point of a lower degree of innovation, that is, a point from which incremental innovation begins to grow. Thus, the changes in product functionalities caused by technological newness vary in terms of the degree of modular innovation. However, radical technology innovation requires path-breaking technological newness in modular innovation compared to path-dependent technological progression in incremental innovation.

Scenario EFG indicates a relatively high change in technological newness in modular innovation, but the change is only expected to bringing a relatively low degree of change to the interfaces and structure of architectural innovation. These types of scenarios have often been described in the literature, where it is highlighted, for instance, that modular innovation has led to developments that leave the overall architecture relatively unchanged (e.g., Chou et al., 2016). By contrast, *scenario HIJ* shows that there has been a lower degree of change in technological newness in modular innovation, but this could lead to a relatively higher degree of change in product structure, which may lead to greater architectural innovation. This variation may occur due to the complexity of the product technology and the nature of a product.

Thus, we argue that modular innovation, from a technology perspective, may not always result in a similar amount and degree of change on the architectural side. However, modular and architectural innovation together affect the degree of radical technology innovation or, conversely, incremental technology innovation.

Our case studies explore examples of the degree of technological newness that triggers different levels of radical product innovations, which can be analysed through the above-described framework. For example, technology like battery packs and battery control systems (i.e., modular innovation) together with changes in product structure (i.e., architectural innovation) in Tesla's Model X have resulted in new functionalities and improved performances of its cars, which leads to radical technology innovation not only in its cars but also in the industry. In addition, modifications and improvements with other modules impact the overall performance through improvements to technology. Thus, the degree of innovation is confined to a few modules but affects the broader architecture. Similarly, in the AVC robot, new functionalities related to modules involving control, navigation and autonomous functions represent a high degree of modular innovation, which leads to change in the interface (and architecture) and results in radical innovation in terms of functionalities and customer utility.

Modules and their interfaces in the product can be used to develop product platforms (Ericsson & Erixson, 1999; Jiao & Tseng, 2000; Ulrich, 1995; Ulrich & Eppinger, 2008), since product platforms are the set of common components, modules or parts from which derivative products can be developed. Understanding product platform strategy helps in developing future product generations. Product platforms can offer benefits when applied successfully. Companies can develop differentiated products by sharing components across a product assortment, so they can reduce development time and cost and system complexity. They can also acquire the ability to upgrade and redesign products. In this study, we observed that in some versions of the Tesla car, dual electric motor drive assembly was used instead of a single motor drive assembly, while most of the other components were still common or shared. This new method of vehicle design makes it possible to build several car models from a common platform.

Our findings suggest that by identifying the modules and the product architecture (interfaces) earlier in the design process, it is possible to reduce the production lead time. This approach helps companies allocate resources earlier in the design process, given that parallel manufacturing of the modules can be carried out instead of manufacturing an entire product in a sequential way. This strategy helps speed up development and help industry be more agile to market demands. For instance, in the Roomba case, once the basic architecture including actuators, sensors and controllers were designed, managers could decide to undertake concurrent developments of the modules in different departments in the company to accelerate the product development.

Modular architectures also support easier service and upgrading, since standardized interfaces enable by adding or replacing a module easy (Ericsson & Erixson, 1999; Ulrich & Eppinger, 2008). In Roomba's case, the number or types of sensors can be varied or replaced to enhance functionality. It is also possible to upgrade Roomba by changing the processor or installing a more powerful suction system due to modular innovation and standardized interfaces. In Tesla cars, the modules in the integrated drive assembly enable the car functionality to be upgraded, for instance the flexible and lengthy electrical cables in a conventional electric vehicle can be replaced to the short and low-loss bus bars. These modifications reduce manufacturing costs and allow design flexibility.

An example may illuminate our understanding further. Through the use of technology driven modular innovation (i.e., the spark plug system), Mazda produced the Skyactiv-X Spark Controlled Compression Ignition (SPCCI) engine that offers two new values— 'better fuel efficiency' and 'less CO2 emission'. This is an example of a micro-foundation-based product innovation. However, the degree to which Mazda's modular innovation in the engine brings in new functionality (incremental) is less than Tesla's high-speed electric engine (radical). Thus, this makes a difference in the degree of product innovation between Mazda and Tesla. Both of these examples originated through the introductions of new modules to a car, rather than 'a new product' in its entirety.

However, as far as sustained competitive advantage is concerned, it does not depend on modular innovation or technological competency alone. Rather, for example, in case of Tesla, it depends on how and to what extent it can control the ecosystem of electric car production and consumption as well as the readiness of society for electric cars. Whether society embraces electric cars greatly depends on supportive institutional conditions and how industry evolves. There are two types of firms; one is a market-driving firm (through new technology and marketing techniques) and the other is the market-driven firm. The aim of a market-driving firm, like Tesla and Apple, is not only to make a new product, but also to create a new industry, that will support a new ecosystem for the product family. These types of companies appropriate value not only by selling product but also by creating a chain of value along the service platform points and ecosystem. They tend to be the driver in both the service platform and technology standard of production process. As a result, such firm may have fewer threats from competitors because they create an industry ecosystem; thus, even though competitors may replicate their technological newness, they cannot replicate the whole ecosystem or the service proposition system.

6.2 Managerial implications

From a strategic product innovation perspective, managers can focus on the distinctive functionalities their companies are pursuing to offer to the market. Thus, managers can focus on strengthening their core technical competencies, organizational fitness and R&D focus in support of initiating product innovation. Our findings suggest a need to connect strategic thinking from the ‘bottom-up’ level of modules and components (although this depends on the type of product). Such an approach can provide not only an opportunity for radical technology innovation but also sustainable product improvement on a continuous basis.

In this study we utilized an engineering approach (system architecting), which provides particularly concrete advice for product design and innovation management. We demonstrated the approach via hierarchical decomposition of products, which is used to facilitate the physical realization of the system in the form of modules and their interfaces. From a management perspective, there are several advantages of applying the engineering approach.

First, it allows us to demonstrate how complexity in products is managed through the hierarchical decomposition of the system and the development of modules and their interfaces. By applying a systems approach, companies can manage the product and its related activities more effectively. This is because the identification of interfaces between domains in the hierarchical system can decrease transaction and coordination costs. This could improve cost/value ratios when renewing existing product lines and provide increased understanding of incurred cost if the market wants new product functions. The system architecting approach can thus be used by firms to manage complexity in the design process and also structure the manufacturing process for new products. By identifying the architecture and required interfaces between the modules, the assembly process and the necessary manufacturing resources can be identified early in the design stage. For instance, a standard module that is common in all versions of the product family can be used to structure the manufacturing process i.e. utilizing automation in factory to achieve economies of scale. For differentiated parts that are used for product customization, a flexible material handling system can be implemented in the factory.

Second, it is possible to introduce new modules that provide new functions in relation to customer requirements. With a systems approach, new technology in the modules that generate new interfaces can be incorporated to address the customer demands either in ‘technology push’ or ‘market pull’ scenarios. For instance, a new module introduction with changes in interfaces can have a great impact on the product’s function. Similarly, companies may be able to take a new market demand (a new desired function) and assess whether and how existing product architectures and interfaces could be modified in order to create such function. This gives an added wholistic and balanced understanding to the management perspective; it is clearly demonstrated in the cases (Table 3 and 5) that the individual components also need a varying degree of interface change when in the product architecture. This would also enable companies to better grasp the complexity in the changes required to the product in order to meet new customer demands.

Third, using a system architecting approach, descriptions at different levels of the hierarchy can be made consistent. For example, the decisions at the lower level could be traced to higher level abstract concepts, such as functions. Therefore, the engineering approach paves the way for translating product idea and structure into marketable functions, and their relationships and hierarchy could be utilized in the decision-making process. These insights complement the extant management literature which lacks discussion on how functions and structure in a product are linked to each other and how the decisions in design process are taken at different hierarchical levels leading to new product development.

Fourth, system architecting makes it possible to redesign and develop multiple system architectures to facilitate product platforms and product family modeling for next generation products. The product architecture in both case studies (see Figure 3 and Figure 6) can be altered by redesigning and using new technology in modules to develop product platforms and product families. Customization can be used to generate more variants in the product using product platforms. Thus, by applying customization in conjunction with technology innovation in design, companies can develop derivative products for the markets and generate more innovations in the future (which is also the case in Roomba which has multiple models in the same product family). Concurrently, the engineering approach is more concerned with design issues, customization, decomposition of the system, interface development and improvements in the core design system. The management approach, on the other hand, is primarily concerned with organizational aspects related to reconfiguring the existing products. This would concern with e.g. knowledge development and know-how for the organization, innovation process restructuring and product development strategies, as emphasized by Henderson & Clark (1990: 17) and Christensen (1997: 120). Based on these insights, we argue that the engineering perspective gives greater depth in managerial discussions related to new product development, providing an informed ground for understanding implications of changes to products to fit or disrupt the market.

Our study also provides several implications for modular innovation. In fact, managers as well as business scholars and students tend to have myopia on product innovation because they often think of innovation of a ‘whole product’ that comprises different bundles of functionalities. However, we argue that it is not always beneficial to think of product innovation as a ‘whole’ or as a ‘complete product’. Rather, it is useful to view product innovation from a micro-foundations perspective using system architecting approach, looking into the component and the modules and thinking about how they can bring in new or radical functionalities. This method demonstrates how a firm can offer a new utility and value to its customers and, thereby, differentiate its value proposition in the market. It should be noted that this approach is most appropriate in technology-driven industries, and gives firms a way to offer next generation technology-based products faster than before, improving the potential to gain and retain competitive advantage.

Finally, modular and integral architectures warrant different project management styles. A modular approach requires more planning during the system-level design phase. This detailed design approach should primarily focus on meeting module performance, customization, cost and schedule requirements. By contrast, integral architecture approaches require less planning and specification during system-level design, but more team integration and coordination are necessary during the detailed design phase. Furthermore, modular product designs facilitate the outsourcing of modules to suppliers with an aim to improve the quality and management of product development. Since the supplier is responsible for manufacturing, development and overall product quality may improve, and the burden on the parent company may be reduced. However, this approach increases the complexity and management of coordination, knowledge transfer, monitoring, intensive communication, planning and governance of the global supply chain. In this case, the role of technologies such as 3D printing and the IoT (Internet of things) could make a significant difference in process management, design and modular innovation.

6.3 Limitations and future research directions

In our study, we have examined a particular product from a product family and presented a generic product description to demonstrate an overarching understanding of the product architecture. Repeat studies on other models of the same product would be beneficial to enhance the reliability of the findings. Our research also explains the modules in product architectures in a simplistic manner without pinpointing the detailed description of the interfaces between modules or suggesting how they could be improved to develop a platform for production. This perspective was pointed out by Sköld and Karlsson (2013) and further studies could focus more on these aspects.

Our study has adopted the engineering perspective and focused on the modular innovation as an antecedent to a process that leads to architectural innovation and ultimately to technological newness. It should be acknowledged that there are other types of progressions that are possible. For instance, modular and architectural innovation could be dealt with in parallel, or product architecture could be the initial starting point in some cases. Furthermore, the progression might follow both ‘market pull’ or ‘technology push’ approaches. In the former, the functionalities required by the markets are determined first, followed by modular innovation, and potential changes in architecture. In the latter logic, modular innovation takes place first, followed by identification of functionalities made possible by modular innovation. While we do not explore these themes in depth in the current study, future research could look into how firms engineer their innovation processes in this regard, and to which type of managerial implications it leads to.

Finally, although we do not highlight the organizational competencies that affect a firm’s decision and ability to pursue different degrees of modular innovation, such competencies are undoubtedly a key success factor. Management’s strategic outlook for developing a new product (i.e., how and by what sort of technological newness it will advance) and how they will position it in the market (Henderson, 2006) are important decisions companies must make. Therefore, further studies could examine how organizations deal with the modular–architectural interface in decision-making and organizing choices. Further studies could also more broadly examine how modular and architectural innovations in product design affect firms’ longer term competitive advantages. For instance, is it possible to create radical newness to individual components (e.g., electric motor), while competing with similar types of architectures. Or does it pay off to create an architecture that other companies cannot replicate and build an ecosystem of modular innovation and related partners around it? We believe that looking closely to the product design architecture and viewing it as part of the broader innovation strategy can provide interesting insights into these and other related questions.

APPENDIX:

Table A1. Summary of the patent data of the Roomba VC robot along with application numbers, dates of patents publications and a description of the patents that represent the new technology

AVC robot subsystems to identify modules in the Roomba 600 series	**Patents (application number)**	**Dates of patent publications**	**Description of the new technology patents that represent new functionality in the systems**
Navigation and behaviour system	US 6,594,844	07/22/2003	• These patents are primarily related to the control system. • Methods of navigation, energy management and predetermined task completion.
	US 6690134	02/10/2004	
	US 6809490	10/26/2004	
	US 7196487	03/27/2007	
	US 7,332,890	02/19/2008	
	US 7,388,343	06/17/2008	
	US 7,441,298	07/05/2012	
	US 7,579,803	08/25/2009	
	US 8,087,117	06/03/2012	
	US 8,380,350	02/19/2013	
	US 8,417,383	04/09/2013	
Sensor system	US 20140257622	09/11/2014	• These patents are related to the sensor system. • Multiple sensors, such as proximity, bump, cliff, infrared receiver and debris sensors, are installed and used to detect and navigate the robot system.
	US 8,742,926	06/03/2014	
	US 7,430,455	07/02/2013	
	US 6956348	10/18/2005	
Main architecture	US 8,474,090	07/02/2013	The main architecture of the robot comprises the housing, wheels, a motor driving the wheels to move the robot across a floor, a control module, an obstacle sensor, and a removable bin.
Cleaning system	US 8,800,107	08/12/2014	There is a rotating cleaning element that is inserted into the cleaning head compartment.
Bumper assembly	US 20140246874	09/04/2014	This patent is related to a robot bumper. It includes a bumper body and a top surface. The bumper body conforms to the shape of a robot chassis.

Table A2. Summary of the patent data of the subsystems identified in Tesla Model X, including patent applications numbers, dates of patents publications and newness in the form of new technologies and new functionalities

Subsystems from which modules are identified in the Tesla car	**Patents (application number)**	**Dates of patent publications**	**Description of the new technology patents that represent new functionality in the systems**
Motor assembly	US 20090121563	05/14/09	• These patents are primarily related to the electric motor cooling system, the rotor design and the lamination design. • These patents claim to bring the following improvements to electrical and mechanical characteristics: improved torque and improved flux distribution for improved efficiency, torque density and high-speed power. • The cooling system can direct coolant to critical motor parts both by way of a pressurized jet and by way of a gravity-feed approach to ensure that the coolant is distributed in an effective way to all relevant motor components.
	US 20100141080	06/10/10	
	US 20100244612	09/30/10	
	US 20110062819	03/17/11	
	US 20110198962	08/18/11	
	CA 2655210	11/04/14	
	US 20140339950	11/20/14	
	US 20140368064	12/18/14	
	US 20150123511	05/07/15	
	US 20150222162	08/06/15	
Thermal management system	US 20100104938	04/29/10	These patents are primarily related to the liquid manifold, and they include dual-mode coolant loops, interfaces with integrated motor assemblies, energy storage systems, radiator and condenser systems, cooling systems and heat exchangers.
	US 20110296855	12/08/11	
	US 20120180997	07/19/12	
	US 20120183815	07/19/12	
	US 20120153718	06/21/12	
	US 20120222833	09/06/12	
	US 20130327511	12/12/13	
	US 20130074525	03/28/13	
Dual-motor drive system	US 20130241445	09/19/2013	• This patent outlines a method for optimizing the torque applied by each motor of the dual-motor drive system of an all-electric vehicle. • The torque adjustments take into account wheel slip and other vehicular operating conditions.
Inverter system	US 20120195087	08/02/2012	This invention relates mainly to the switching of semiconductor power devices. Its purpose is to selectively decrease excessive voltage overshoot during the fast turn-off of hard-switched high voltage semiconductor power devices. The apparatus includes an inverter, which couples a high-side switch with a low-side switch.
Main control system	US 20140257613	09/11/2014	• This is related to a control system for an all-wheel drive electric vehicle. • This system has different configurations to control the various electric vehicle systems, such as traction control, electric motor, the thermal management system, the ESS and the inverter. • It receives signals from various sensors in the car system.
Charging system	US 20090167254	07/02/2009	These patents are primarily related to the charging system of the electric vehicle.

	US 20150039255	02/05/2015	These patents claim to provide multi-mode charging, charging time optimization, trickle charging, fast charging, low-temperature charging, improved charging efficiency and a protection system for the battery pack.
Battery pack	US 20100316894	12/16/2010	• These patents are specifically related to the battery pack; they introduce new systems and components and improve existing ones. • These patents are primarily related to battery management, i.e., improving safety systems, increasing battery life and reducing damage during charging.
	US 20140178722	06/26/2014	

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