Managing openness in high complexity innovation projects: Evidence from the automotive sector

TITLE

MANAGING OPENNESS IN HIGH COMPLEXITY INNOVATION PROJECTS: EVIDENCE FROM THE AUTOMOTIVE SECTOR

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ABSTRACT

Despite prior conceptual work arguing that complex innovation projects should be managed within the boundaries of the focal firm (i.e., closed innovation), recent empirical evidence shows that a variety of complex innovative products have been developed through the collaborative efforts between the focal firm and its business partners (i.e., open innovation). To address this lack of congruity between theory and practice as well as the dearth of project-level research on open innovation, this paper aims to empirically explore the relationship between project complexity and open innovation. Drawing upon a qualitative case study involving a pioneering electric vehicle manufacturer, this study explores the extensive B2B collaborations involved in the development of complex products and system integration efforts that span three different stages (i.e., ex-ante integration, co-development, and ex-post integration). The study aims to shift the current consensus in the innovation literature that either negates or does not explicitly accept the possibility of openness for complex projects towards acknowledging, analyzing and explaining the management of open innovation for complex projects.

KEYWORDS

Open innovation; problem solving; product design; project complexity; case study; system integration.

1. INTRODUCTION

In the current highly competitive business environment, firms are increasingly collaborating with other firms or organizations (e.g., suppliers, buyers, universities, government, or competitors) to reduce costs, improve time-to-market, boost innovation performance, and achieve competitive advantage (Du, Leten, & Vanhaverbeke, 2014; Faems, Van Looy, & Debackere, 2005; Majchrzak, Jarvenpaa, & Bagherzadeh, 2015; Markovic & Bagherzadeh, 2018). Accordingly, a recent study showed that more than 70% of the surveyed firms embraced open innovation by involving other firms or organizations in their innovation projects (Majchrzak, Bagherzadeh, & Brunswicker, 2016). Open innovation can be defined as "a distributed innovation process based on purposively managed knowledge flows across organizational boundaries" (Chesbrough & Bogers, 2014, p. 17).

In the innovation and marketing literatures, there is a plethora of studies on open innovation in business-to-business (B2B) contexts, but most of them have been conducted from the firm-level perspective (e.g., Antons, Kleer, & Salge, 2016; Markovic & Bagherzadeh, 2018; Randhawa, Wilden, & Hohberger, 2016). Whilst studying open innovation at the firm level can bring valuable insights on how to manage firm openness to business partners, "neither the practice of nor the research on open innovation is limited to the level of the firm" (West, Vanhaverbeke, & Chesbrough, 2006, p. 287). Instead, the topic of open innovation in B2B contexts should be enriched by project level studies (Antons et al., 2016; Randhawa et al., 2016). The reason is that not all innovation projects, even within the same firm, are alike (Brunswicker, Bagherzadeh, Lamb, Narsalay, & Jing, 2016; Du et al., 2014). They can have different attributes, such as strategic importance, complexity, and type of knowledge required (Afuah & Tucci, 2012; Cassiman, Di Guardo, & Valentini, 2010; Felin & Zenger, 2014). Of these attributes, scholars have argued that project complexity, which refers to the degree of interdependency between numerous components, elements, and sub-systems involved in the project (Fernandes & Simon, 1999), is one of the most important as it can condition the whole open innovation process (e.g., Almirall & Casadesus-Masanell, 2010; Nickerson & Zenger, 2004).

The consensus in the innovation literature holds that simple and low-complexity projects are easily amenable to open innovation arrangements, such as R&D contracts or innovation contests (Felin & Zenger, 2014; Nickerson & Zenger, 2004). The argument supporting this view is that simple and low-complexity projects can be easily decomposed into separate sub-systems or modules, which can be assigned to business partners (Felin & Zenger, 2014; Fujimoto, 2007). Conversely, complex innovation projects tend to be managed within the boundaries of the focal firm (i.e., closed innovation) (Felin & Zenger, 2014; Fujimoto, 2007; Nickerson & Zenger, 2004). There are two main arguments supporting this view. First, decomposing complex innovation projects into separate sub-systems or modules, assigning them to business partners, and then integrating the solutions proposed by such business partners, is challenging and can inhibit the successful completion of innovation projects (Fujimoto, 2007). Second, complex innovation projects require extensive knowledge sharing, which is more feasible within the boundaries of the focal firm. Deep knowledge sharing with business partners, apart from being more difficult, is also risky, as it implies disclosing critical knowledge to them (Felin & Zenger, 2014; Nickerson & Zenger, 2004). Despite this consensus in the innovation literature, some recent empirical evidence shows that a variety of complex innovative products, ranging from technologies for rendering animations (Brunswicker et al., 2016) to commercial aircrafts (Tang, Zimmerman, & Nelson, 2009), have been developed through the collaborative efforts between the focal firm and its business partners. Thus, there is an apparent lack of congruity between such empirical evidence and the consensus established in the innovation literature regarding the management of complex innovation projects.

To address this lack of congruity, and the aforementioned dearth of project-level research on open innovation in B2B contexts, this papers aims to empirically explore the relationship between project complexity (one of the most important project attributes) and open innovation by developing an understanding on how firms manage their collaborations with other firms or organizations to deliver commercially viable complex innovations. Drawing upon a single qualitative case study of Mahindra Reva, a pioneering Indian electric vehicle (EV) manufacturer, we provide empirical evidence around the complex architecture of EVs; the B2B collaborations involved in the product development; and the system integration efforts that span three different stages (i.e., ex-ante integration, co-development, and ex-post integration). The paper makes four main contributions. First, by considering project attributes (i.e., project complexity), we empirically contribute to the open innovation field, which is dominated by firm-level studies. Second, in contrast with the above-presented consensus in the innovation literature, we show that firms can embrace open innovation with business partners in complex projects, and we discuss how firms should do it in order to take the greatest advantage from it. Third, we show that system integration is a critical activity in open innovation that requires further scrutiny in the literature. We suggest that the higher the project complexity, the greater the importance and difficulty of system integration. Fourth, we find that, in early stages of technology trajectory (see Alexy, George, & Salter, 2013), firms do not fully protect their knowledge, but engage in a selective knowledge sharing with other firms or organizations to solve complex innovation problems.

2. THEORETICAL BACKGROUND

To study the relationship between project complexity and open innovation, we draw on two related literature streams: the problem-solving view and the product design perspective. The central concepts to these literature streams (i.e., problem/project and product, respectively) are defined as follows. A problem/project consists of "elements, choices and knowledge sets that must be creatively recombined to compose valuable solutions" (Felin & Zenger, 2014, p. 916), while a product is a tangible output of a specific innovation problem/project.

2.1 The problem-solving view

The problem-solving view argues that different projects, in terms of complexity, demand different solution search approaches (Felin & Zenger, 2014; Nickerson & Zenger, 2004). According to Gavetti and Levinthal (2000), there are two possible solution search approaches: directional (also known as "trial and error") and cognitive (also called heuristic). The directional solution search is guided by experiences or feedback from previous trials (Gavetti & Levinthal, 2000; Nickerson & Zenger, 2004). This type of solution search involves implementing one solution design at a time, observing whether the solution value increases or declines, and adjusting the solution design accordingly (Gavetti & Levinthal, 2000; Nickerson & Zenger, 2004). Conversely, the cognitive solution search consists of a process in which solution seekers evaluate the potential value of a solution design before implementing it. This evaluation is made based on a cognitive map, which is a simple representation of the solution space. The cognitive map explains the required knowledge sets and their underlying interactions required to solve the problem (Gavetti & Levinthal, 2000; Nickerson & Zenger, 2004). According to Nickerson and Zenger (2004), the cognitive solution search is the preferred approach for dealing with complex problems, whereas the directional solution search is preferable for addressing simple problems. As complex problems consist of numerous, highly-interdependent elements, choices and knowledge sets, directional solution search would be extremely costly and time-consuming, and thus inappropriate for dealing with such problems.

Developing a proper cognitive map for an efficient cognitive solution search requires deep interactions and extensive knowledge sharing between multiple problem solvers, who are experts in a specific field, to ensure that they have access to relevant knowledge sets (Nickerson & Zenger, 2004). However, these interactions and knowledge sharing create the possibility of opportunistic behavior among problem solvers because of seeking self-interest with guile (Williamson, 1993). This means that one problem solver can pursue their own goals at the expense of another problem solver's knowledge. Such opportunistic behavior is perceived as more dangerous when problem solvers have the fear of knowledge leakage (Heiman & Nickerson, 2004; Qiu & Haugland, 2019). Knowledge leakage (i.e., the extent to which the problem solvers' knowledge is unintentionally transferred to other problem solvers beyond the scope of the problem solving agreement (Jiang, Li, Gao, Bao, & Jiang, 2013)) can be present in various types of B2B relationships, ranging from strategic alliances to collaborations between buyers and suppliers (Khanna, Gulati, & Nohria, 1998; Norman, 2004; Soriano & Parker, 2012).

Therefore, potential opportunism can discourage problem solvers from sharing knowledge with each other, leading to an inappropriate cognitive map, which can hinder the cognitive solution search. As a way to reduce potential opportunism, the problem-solving perspective suggests relying on problem solvers within the boundaries of the focal firm (i.e., internal problem solving or closed innovation). Thus, according to the problem-solving perspective, closed innovation is preferred to open innovation when solving complex problems.

2.2 The product design perspective

Drawing on the work by Henderson and Clark (1990), Ulrich (1995) argues that product design/architecture consists of three interrelated aspects: (1) the arrangement of functional elements; (2) the relationship between functional elements and physical components; and (3) the interfaces connecting the physical components. In line with this definition, the product design perspective (Fujimoto, 2007; Ulrich, 1995) argues that there are two types of product architecture: modular and integral (see Figure 1).

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On one hand, the modular architecture is characterized by a "one-to-one correspondence between functional and structural elements" (Fujimoto, 2007, p. 84). The structural elements (i.e., components and sub-systems) are functionally complete, while the interfaces are simple and standardized (Fujimoto, 2007). A crucial implication of these characteristics is that structural elements can be designed and developed independently by multiple actors with minimal interactions and knowledge transfers (Fujimoto, 2007; Simon, 1962).

On the other hand, the integral architecture involves a highly complex (i.e., many-to-many) mapping between functions and structural elements (Fujimoto, 2007). The structural elements are functionally incomplete, as they interact with other elements to perform specific functions (Fujimoto, 2007). The interfaces are not standardized and are closely coupled with the structural elements (Ulrich, 1995). Consequently, the components and sub-systems cannot be designed and developed independently from one another (Fujimoto, 2007; Ulrich, 1995). While the outsourcing of the manufacturing of these components and sub-systems to third parties is possible, their design and development, as well as the overall system design, must be "contained within one company" (Fujimoto, 2007, p. 86).

2.3 Intersection between the problem-solving view and the product design perspective

As both the problem-solving view and the product design perspective build on the seminal work by Simon (1962), parallels between the two strands of the literature become apparent. First, there is a clear correspondence between complex problems and integrated product architectures. Insofar the development of a product represents a complex problem, the respective product will require an integrated architecture. Second, both literature streams concur that internal development (i.e., closed innovation) is required for complex products with integrated architectures. While the problem-solving view proposes opportunistic behavior (Nickerson & Zenger, 2004) and knowledge transfer difficulties (especially in the case of tacit knowledge) (Felin & Zenger, 2014) to justify the unfeasibility of openness for complex problem solving, the product design perspective suggests that a mixing-and-matching of components and sub-systems designed independently by multiple firms is only possible for products with modular architectures (Fujimoto, 2007).

As the modular and the integral product architectures represent the two extreme options (Fujimoto, 2007), Lim and Fujimoto (2019) propose the quasi-integral product architectures, which involve off-the-shelf components that are ex-post incorporated into an internally integral product architecture. Despite this important conceptual advancement, there remain two ambiguous areas in the product design literature. First, it is unclear why might firms be able to incorporate common off-the-shelf components within a coherent integrated product design, while facing insurmountable difficulties in integrating innovative components and sub-systems designed by third parties. Second, while Lim and Fujimoto (2019) hint (but do not explicitly acknowledge) that open product development and innovation may be feasible for integrated product architectures, how firms manage openness in the development of complex products with integrated architectures remains hitherto a black box.

3. PROBLEM FORMULATION AND RESEARCH OBJECTIVE

The above reviewed strands of literature suggest that an open approach to complex problem solving generates two main costs: opportunism cost and integration cost. This implies that closed innovation, which does not involve these costs, is the preferable approach to solving complex problems. Surprisingly, however, empirical evidence shows that a wide variety of complex problems has been solved successfully through open innovation (i.e., by relying on contributions from a broad set of business partners). Such empirical evidence comes from the contexts of commercial aircrafts (Tang et al., 2009), electronic components and devices (Morris, 2017; Smith, 2015), and drug discovery and development (Brunswicker et al., 2016), among others. For example, in the context of commercial aircrafts, Tang et al. (2009) showed that, despite the high levels of complexity that producing a Boeing Dreamliner 787 implies, a wide networks of Boeing's business partners (e.g., Mitsubishi, KAL-ASD, Spirit, Alenia) have designed and developed the key sub-systems independently (e.g., wings, wingtips, thrust engines, forward and center fuselage, horizontal stabilizer tail), while Boeing has handled the overall design and system integration. As this aircraft is one of the most innovative and successful commercial aircrafts to date (Smith, 2015), it seems that open innovation can provide a set of benefits to complex problem solving than can exceed its costs (Hottenrott & Lopes-Bento, 2016).

In open innovation in the B2B context, the focal firm (e.g., Boeing) purposefully collaborates with different business partners (e.g., competitors, suppliers, distributors) to solve its innovation problems (Gurca & Ravishankar, 2016; Majchrzak et al., 2015). Collaborating with different business partners is likely to provide the focal firm with a set of previously inaccessible external resources (e.g., ideas, skills, technologies, and/or knowledge) (Dyer & Singh, 1998), which can improve the quantity, quality, and diversity of the focal firm's resources needed for solving its innovation problems (Eisenhardt & Schoonhoven, 1996). Accessing relevant external resources is especially important for solving complex problems, as an individual focal firm is not likely to have all the required resources to do so (Felin & Zenger, 2014; Lehtinen, Aaltonen, & Rajala, 2019). Moreover, accessing relevant external resources can help the focal firm reduce the product development costs and improve the time to market (Eisenhardt & Schoonhoven, 1996). Based on the above empirical evidence and line of reasoning, we argue that firms can take advantage of open innovation for complex problem solving by breaking down their innovation projects into sub-systems designed and developed independently by their business partners, if they can manage to reduce opportunism and integration costs. Thus, the main goal of our study is to understand how firms manage extensive collaborations with their business partners for delivering commercially viable complex innovations.

4. METHODOLOGY AND DATA ANALYSIS

4.1 Methodological approach

As the existing knowledge on managing open innovation in highly complex projects is limited (e.g., Felin & Zenger, 2014; Fujimoto, 2007; Pisano & Verganti, 2008), a qualitative, exploratory research approach has been adopted (Yin, 2015). Concretely, we used the single case study approach to obtain a deeper understanding of the phenomenon and its context by combining different sources of evidence (Yin, 2015). The single case study approach is especially appropriate for studying largely under-researched topics with a relative lack of robust theory (Yin, 2015), as it allows to analyze the patterns and the case more in-depth, compared to multiple case studies or quantitative research (Eisenhardt & Graebner, 2007).

This study is longitudinal in nature, and applies a retrospective processual approach (Halinen & Törnroos, 2005). Informants have been referring to stories that have occurred in the past, and thereby used a retrospective lens on events. This allowed us to collect data spanning a longer period of time.

4.2 Research setting

The case company was Mahindra Reva, and it was chosen based on its recognized status as an EV pioneer. The origins of the current Mahindra Reva company trace back to July 2000, when the Maini Group established the Reva Electric Car Company (RECC). The Maini Group is a Bangalore-based family-owned business that, among others, supplies high-precision automotive components and assemblies, and manufactures electrically operated material handling equipment (e.g., forklifts). In 2001, the company launched its first EV – the Reva (or G-Wiz, as it was known in Europe). The selling price of the Reva was approximately US$ 5,000, and it was sold until 2012 in 25 countries. Recognizing that RECC needed a capital infusion to fulfil its growth potential, the Maini Group sold in 2010 a majority stake of the company to the Indian automaker Mahindra & Mahindra Ltd (M&M). Following the transaction, RECC became the Mahindra Reva Electric Vehicle Company (Mahindra Reva). Despite the rebranding, Mahindra Reva was not incorporated under the M&M umbrella and remained an independent entity. In March 2013, Mahindra Reva launched its new model - the Mahindra e2o, which had a price tag of approximately US$ 12,000.

Table 1 illustrates the complex architecture of Mahindra Reva's EVs (i.e., Reva/G-Wiz and e2o). Each one of five main EV functions are delivered through the interaction of three or more physical components. The size and power of the battery pack determines not only the top speed and driving range, but also the aesthetics of the vehicle. Enhancing the battery pack to increase speed and driving range also influences the position (e.g., front, back or underneath the front seats) of the batteries as well as the car's interior space. The regenerative brakes serve a dual function: (1) they reduce speed and stop the moving vehicle; and (2) when the brake is applied, the system produces kinetic (mechanic) energy, which is transferred to the engine. Consequently, the EV engine serves multiple functions as well. In its normal function, the engine is a consumer of electric energy, which it turns into kinetic energy to put the vehicle in motion. Its power and efficiency directly influence the top speed and driving range. Moreover, in the reverse function, the motor is a generator of electric energy as it turns the kinetic energy coming from the brakes into electricity that is then stored in the battery, thereby enhancing the driving range. Similarly, the Intelligent Energy Management System (IEMS) has numerous functions: (1) it continuously monitors the battery cells and the power consumption; (2) it equalizes the use of individual battery cells using algorithms that improve the driving range and extend the battery life; (3) it controls the charger and the EV motor; (4) it controls the instrument cluster; and (5) it sends data back to the company and allows the remote servicing of the car through a telematics system. The plastic external body clearly determines the aesthetics of the car. In addition, the weight and aerodynamics of the car body affect the top speed and driving range, while the structural resistance of the plastic panels influences passenger safety in case of crash. Similarly, the tubular car frame replacing the typical chassis determines the shape and volume of the car, but also the safety in case of accidents. All this shows the complexity of Mahindra Reva's EVs.

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Despite this apparent complexity, Mahindra Reva adopted an open approach for the development of its two EV models due to very compelling reasons (Gurca & Ravishankar, 2016). First, facing important resource constraints, the company did not have any manufacturing capabilities. Most of its resources had been tied up in extensive R&D capabilities and a very frugal assembly line, which meant that all components and sub-systems had to be manufactured by external suppliers. However, as Mahindra Reva was one of the true pioneers of the EV industry in the late 1990's, much of the EV-specific technology was yet to be developed. In an era dominated by internal combustion (IC) vehicles, there were no EV-specialized suppliers available at the time. Thus, the company had to engage in extensive collaborations with non-specialized suppliers. Second, as the company's strategy focused on providing the most affordable EVs in the world, Mahindra Reva had to ensure that the designs of components and sub-systems were compatible with the suppliers' existing production lines to avoid tooling costs as much as possible. Had Mahindra Reva chosen to rely on original designs developed internally, then suppliers would have likely needed to adapt their production lines to deliver the required components and sub-systems, thereby driving up the overall cost of the vehicle (Gurca & Ravishankar, 2016).

4.3 Data collection

The data has been collected in 2013, primarily through semi-structured, face-to-face interviews conducted in Mahindra Reva's headquarters and production facilities in Bangalore, India. In total, 48 interviews with informants from different hierarchical levels in the firm have been conducted (see Table 2). The interviews were conducted in English, and were tape recorded (with two exceptions) and transcribed verbatim. They lasted 50 minutes on average, and the discussions were based on open-ended questions that allowed for obtaining rich and thick data on innovation projects and their complexity. The interviews covered the development of

Mahindra Reva's two main EV models (i.e., Reva/G-Wiz and e2o), and all the subsequent variants of each model.

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In addition, secondary data has been collected through archival materials, such as the firm's internal reports, website, newsletters, marketing communications, product presentations, customer feedback, newspaper and magazine articles, and social media. This secondary data represented events related to Mahindra Reva spanning the last two decades of their business activities, and thereby helped us enrich our understanding of the primary data.

4.4 Data analysis

The data analysis contained three stages: open coding; axial coding; and selective coding (Creswell, 2013; Goulding, 2005). In the open coding stage, through a line-by-line reading of the transcribed text, we identified patterns in the data, labeled concepts, and examined their properties. In the axial coding stage, to find explanatory relationships between the concepts, we compared them against each other and clustered them into categories and subcategories (Creswell, 2013). Finally, in the selective coding stage, to theorize the observed relationships between the concepts, we compared the previously established categories and subcategories among them and against the already existing literature (Goulding, 2005). As we performed a constant comparative analysis between the already analyzed data and the posteriorly collected data, the processes of data collection and data analysis partially overlapped (Eisenhardt, 1989). This iterative approach enables us to increase the robustness of our findings (Creswell, 2013; Eisenhardt, 1989; Goulding, 2005).

5. FINDINGS

Our case study analysis revealed that the challenges posed by an open approach to the design and development of complex products may be addressed by a multi-stage process of system integration (i.e., ex-ante integration, co-development, and ex-post integration), which we describe in detail below.

5.1 Ex-ante integration

5.1.1 Hierarchical product architecture

According to our case data, the system integration process is facilitated by the hierarchical nature of early designs. A system (i.e., a group of interacting project elements) is considered to be hierarchical when it is built from separate sub-systems which function as a whole (Simon, 1962). The main benefit of hierarchical systems is that they consist of (relatively) stable intermediary states. Consequently, hierarchical systems of any kind (e.g., physical, biological, social) evolve faster than the non-hierarchical ones with a comparable size and tend to (self-) perpetuate and displace non-hierarchical systems (Simon, 1962). At Mahindra Reva, the overall EV design was divided into key sub-systems (e.g., battery pack, tubular frame, plastic external body parts) corresponding to knowledge domains and capabilities of independent suppliers (See Table 3).

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This hierarchical architecture did not reduce the complexity of interactions between sub-systems, thereby making the EVs modular or easily decomposable. The interactions and interdependencies *among* the main sub-system remained highly complex, despite limited interactions *within* certain sub-systems (see Simon, 1962). The aim of the hierarchical architecture is to establish conceptual boundaries for future collaborations with suppliers.

Within the overall hierarchical system (i.e., the vehicle), some key sub-systems had a modular design. The concept of modularity is rooted in the computer industry (Baldwin & Clark, 2000), which served as inspiration for Mahindra Reva too:

> *"I got the idea of modularity after examining the design of electronics. I remember changing the electronics so many times during our development process… Unless you use a modular design, you won't be able to keep the pace with the latest developments in*

electronics and you'll never be able to utilize the entire value that these developments can provide." (CEO)

Modular design reduces the cost and difficulty of the integration process (Fujimoto, 2007) and, at the same time, allows for directional, trial and error solution searching (Nickerson & Zenger, 2004). Thus, the company used a hierarchical architecture for the overall complex system (i.e., the vehicle), which consisted of several highly interdependent sub-systems, while aiming for modular design at sub-system level wherever possible.

5.1.2 Flexible system designs

As Mahindra Reva's strategy focused on affordable EVs, the company designers aimed to rely as much as possible on the elements that were readily available off-the-shelf or could be provided by suppliers without significant tooling costs. Consequently, Mahindra Reva designers anticipated that important ex-post design integration efforts would be required due to the inherent design misalignments of components and sub-systems originally developed for other projects and tried to produce very flexible early designs with details that could be adjusted during the development process. According to our informants, the key feature of *flexible design* is that it allows for future changes and alterations without significant reworking of the overall system design:

> *"When I am working on my designs, I go and look at design elements such as air vents, buttons, controls, which are available on our existing models or even on IC cars and try to use some of the existing or standard shapes and characteristics. [...] Of course, this can affect the uniqueness and originality of the interior, but I try to push the styling with the general volumes and to keep these elements quite simple. I make sure that they are at least inspired by existing ones to make sure that suppliers would be able to provide something without important tooling costs."* (Front-line employee - Styling)

Our informants also underlined the importance of appealing, original interior and exterior designs, although they never shied away from admitting that they focused on practicality and affordability. Flexible early designs provided sufficiently precise guidance towards the development of aesthetically attractive products, while allowing the company to proactively reduce manufacturing costs as well as the cost and duration of ex-post integration:

> *"We always look to see whatever parts are available on the market. If we can find an off-the-shelf part, or tweak a little bit an existing part, or adjust our design accordingly we can save a lot of costs. We are not rigid in our designs. Developing a new part as per our designs can take months and cost [tens of thousands] of rupees. There is no point in doing that if we can make a slight modification to our design and use a part which is already available without any development and tooling costs."* (Senior manager – R&D)

The company's flexible designs relied on an extensive knowledge of prior designs and available components. Such knowledge allowed the designers to avoid very vague designs, while maintaining sufficient flexibility to incorporate several plausible sub-system designs within the overall system design, as indicated by the quotes below:

> *"We don't have to reinvent the wheel for every single part. I always tell my guys: let's see the benchmarks. Then we can map out what we already knew and what we have learned from the benchmarks and combine the two. This helps us adjust our design to the existing constraints. On the one hand, we have the cost in mind and, on the other hand, the quality and the customers' expectations."* (Mid-level manager – R&D)

and

> *"Engineers and stylists love to work at something new. Sometimes we don't have that luxury here. We tend to use off-the-shelf components and we try to integrate them into our design."* (Mid-level manager – R&D)

5.2 Co-development

As open innovation is a collective process involving multiple contributors (Chesbrough & Bogers, 2014), the co-development of components and sub-systems can prevent possible integration problems at later innovation stages. By co-development, we refer to the collaborative design and development efforts of the focal firm and its multiple business partners. Co-development is noticeably different from a typical outsourcing agreement. The former involves joint processes of sub-system design and development, while the latter implies that the sub-system design and development is the oeuvre of either the focal firm or the external business partner working separately.

Our analysis revealed that, in numerous collaborations involving a joint design and development of EV-specific components and sub-systems, Mahindra Reva provided expertise and knowledge in EV technologies while its business partners contributed with knowledge specific to industries tangentially related to EVs such as electronics and aerospace. The purpose of these knowledge transfers was either generating new knowledge applicable to EVs or enabling suppliers to manufacture EV components on existing lines or with minimal tooling costs.

According to the accounts shared by our respondents, Mahindra Reva's initial knowledge base in EV technologies was developed through the collaboration between the Maini Group (Mahindra Reva's original corporate brand) and a US-based vehicle design, system engineering and component supplier for the global automotive industry. The knowledge sharing was achieved by deputing key personnel with complementary skills and expertise from the Maini Group to the US. Among the staff deputed to the US partner were one of the founders and former CEO, the head of prototypes, and several engineers who had experience in the development of electric forklifts and, thus, knowledge in battery management and production processes. Similarly, Mahidra Reva dispatched its engineers to a supplier's production lines in order to co-develop the company's original tubular spaceframe structure (i.e., EV chassis). This collaboration involved a co-learning process leading to the development of pioneering knowledge between Mahindra Reva and its supplier:

> *"We are the one of the very few companies in the world using spaceframe structures for our cars. We needed to learn how to make space frames for the automotive industry. […] Our supplier knew steel and welding and had production capabilities. We understood the levels of stress and mechanical vibrations the spaceframe will be subjected to, the required reliability in case of crash, and the complexity of the vehicle context. We transferred all our knowledge by deputing our experts to their lines when we were building the first prototypes. There was an interaction and co-learning process in order to ensure the frames will have the required reliability in case of crash and last for 15-20 years."* (Senior manager - Operations)

Another example of co-development is related to the EV chargers, which were developed in collaboration with a US-based company. At the time of the collaboration, EVs were in their infancy but the business partner recognized the commercial potential of the association with an EV-maker.

> *"In the case of the chargers we worked with a US-based company and created a joint technology tie-up which helped us reduce development costs by some 50%. This company was performing very well in the aerospace and defense industries. They were interested in entering the automotive industry but had no expertise in this sector. We had automotive expertise, while they were very experienced with electrics and electronics, so it was a mutually beneficial relationship."* (CEO)

Moreover, according to our informants, even ordinary and straightforward components such as the tires had to be adapted to the particular requirements of EVs. As the supplier had no knowledge regarding EVs and Mahindra Reva was not knowledgeable in tire rubber manufacturing, the solution emerged from a collaborative experimentation process. Eventually, the knowledge gained from the collaboration with Mahindra Reva was implemented in the supplier's core business:

> *"If you use normal tires on EVs about 20% of the energy is lost. The tire manufacturers said they do not have a solution for our problem. We believed that adding more silicon in the tire composition could help. So, we started testing tires with different compositions until we managed to reduce the energy loss to 2-3%. [...] We were the first to introduce silica tires on our cars in India. Today, our supplier provides silica tires for IC cars too."* (Senior manager - Testing)

Our informants also reported instances when the co-development process involved more than two business partners. One such instance involved the development of a new technology for the moulding of the exterior body panels. In order to run experiments with a new moulding process, the resources (i.e. knowledge, tools, and machinery) of three co-developers were required. This multi-lateral co-development was driven by the business partners' mutual interest in developing the technology in question:

> *"We're looking to replace the thermoformed body panels with LFI [Long Fiber Injection] moulded parts and we conducted some experiments which involved two of our suppliers. We worked initially with our proto[type]-shop and we made a tool to produce an exterior ABS [Acrylonitrile Butadiene Styrene] skin. We took that tool to [Supplier 1] and using their machinery and our tool they managed to make the part. Then we took the part from [Supplier 1] to [Supplier 2], which already has a mould for our existing parts. We put the part made at [Supplier 1] in [Supplier 2]'s mould and added the LFI structure on the back of the ABS skin. Luckily, [Supplier 2] is showing a lot of interest in pushing this technology so they were very happy to help us out. Aside from the equipment, [Supplier 2] also provided some inputs about how to improve the process based on their experience*

with plastics. Their inputs helped us reduce the weight of our component." (Mid-level manager – R&D)

Since the lead-acid battery supplier has been working exclusively with IC car-makers, it had no experience in developing large battery packs as those required by EVs. Our respondents felt that the prior experience with electric forklifts, and more importantly the knowledge derived from the experimentation and the tinkering involved in prototype development, constituted the key elements Mahindra Reva was bringing into the collaboration with the battery supplier:

> *"The first battery packs our supplier delivered could be used to drive the EV for 1 km. They were not knowledgeable enough in chemistry. We had to work with them for about two years until they got the chemistry right and managed to fully develop the battery packs."* (Senior manager -Testing)

In this line, Mahindra Reva's engineers developed engine-testing equipment, which was later transferred to the supplier to ensure that the engines met the required standards.

> *"Although our supplier was very good at manufacturing standard motors [for household appliance], they didn't have the capability to deliver according to our requirements. We had to work together to develop all the components. We also did the testing together. Today, the supplier uses the dynamometer testing equipment developed in-house by us. We held the supplier's hand in the areas where they didn't have the expertise and helped either with knowledge, design, or equipment. However, the suppliers did have the core production capability, which we did not have. We actually had complementary strengths and the collaboration helped us both to do things much better and cheaper."* (CEO)

Overall, as the company became more established and knowledgeable within the EV segment, it tried to develop and implement practices that enabled and facilitated the process of co-development. Although Mahindra Reva collaborated with several international business partners (e.g., US- and UK-based firms), the company preferred to collaborate with business partners located in their immediate geographical proximity. In addition to reducing logistics costs, geographical proximity facilitated the knowledge sharing required in the co-development process. Prior research (e.g., Audretsch & Feldman, 1996) argued that inter-organizational information exchange and knowledge sharing, especially tacit knowledge, are limited by geographical boundaries. Tacit knowledge, or knowledge which cannot be verbally articulated (Polanyi, 1966), can be shared only by socialization processes such as observation, practice, interactions or other forms of shared experience (Nonaka, 1994). Despite recent IT progresses that have significantly reduced the cost of information exchanges (Audretsch & Feldman, 1996), the extensive shared experiences needed for tacit knowledge sharing generally require a shared physical presence. Although firms can overcome geographical limitations in the process of tacit knowledge sharing by deputing experts to the lines of their business partners, spatial proximity supports socialization and, thus, tacit knowledge sharing. Similar ideas are eloquently captured by our interviews:

> *"For the windshield frame in the back, we had to choose between a supplier in Pune and one, here, in Bangalore. We went with the local supplier and this helped us a lot with some design changes we had to make after the supplier had started working. Because the supplier was nearby and we worked closely together, we managed to incorporate the changes reasonably fast and smoothly. The supplier also provided a lot of useful inputs. For example, we intended to bond [i.e. glue] the part to the space frame [i.e. chassis] but the supplier offered to provide a fastening system. Their suggestion eliminated the costs with the sealant and improved the assembly times because there was no drying time. [...] If the same thing had happened with the supplier in Pune, I think it would have been very difficult to manage the situation because of the distance..."* (Senior manager – Sourcing and Supply)

Our findings regarding the importance of geographical proximity in the co-development process are also supported by the observation that some of Mahindra Reva's Western business partners were replaced by local companies. For example, the US-based charger supplier and the UK-based lead-acid battery supplier were substituted by Indian companies (see Table 3).

Another practice facilitating component and sub-system co-development was refusing to actively protect proprietary knowledge. Some suppliers derived significant benefits from the knowledge developed during the collaboration with Mahindra Reva. Over time, the co-developed technology allowed these suppliers to find other clients and significantly increase sales. Generally, Mahindra Reva did not object to its suppliers exploiting the knowledge and technologies resulting from co-development collaborations. Mahindra Reva believed that if suppliers expanded their client portfolios, they would achieve economies of scale that would then transfer to Mahindra Reva's EVs:

> *"We are happy when our suppliers expand their business due to the knowledge transferred by Mahindra Reva because we also get to benefit from their economies of scale by purchasing our parts at lower costs. The more knowledgeable and diversified [in terms of clientele] our suppliers become, the more cost and quality advantages we get."*
> (Senior manager - Operations)

5.3 Ex-post integration

Although Mahindra Reva anticipated the need for system integration efforts via ex-ante measures, such as flexible early designs, and tried to reduce the costs and difficulty of integration by co-developing sub-systems and components with suppliers, further ex-post integration actions were required after the design and development of such sub-systems and components. Ex-post integration at Mahindra Reva relied on: (1) system design alignment and integration capabilities; and (2) using software as sub-system integration tool.

5.3.1 Design alignment and integration capabilities

When it first transitioned from lead-acid to Li-ion batteries, Mahindra Reva faced a major integration problem. At that time, there were no specialized suppliers providing big Li-ion batteries that could be used for vehicle propulsion. However, Li-ion batteries had been developed to power small portable electronic devices. Mahindra Reva's engineers had to develop big battery packs weighing up to 250 kg by putting together individual Li-ion cells weighing about 50 grams each. The transfer of Li-ion technology to the EV context did not pose any chemistry problems as in the case of lead-acid batteries. This time, the challenge was wiring together and monitoring thousands of battery cells. The energy had to be consumed evenly from all battery cell and not sequentially (i.e., one cell after another) to extend the battery cell life and improve performance. In order to address this problem, Mahindra Reva engineers placed microchips on each battery cell in order to transmit the information through radio frequency, thereby making the battery sub-system wireless (Secondary data: Maini, 2013).

Design integration was equally important from an aesthetic perspective. This idea is underlined by a designer's perspective capturing the challenges stylists face in their attempt to develop an original and pleasant car design, while relying on a multitude of components borrowed from other designs:

> *"This handle is from Dacia Logan. This part is from a Chinese supplier. This is from Great Wall Motors. This is a Mahindra Scorpio handle. These buttons are adapted. The speakers and the sun visors too. This lamp is adapted. This handle here is a carry-over part. We borrow parts from everywhere in order to reduce costs. Obviously, the challenge is to keep the design attractive after all this. We made the concept first [i.e., ex-ante flexible designs] and then started adapting it. This way we managed to retain the intended styling. For example, the control module is now a three-piece module. Initially, we wanted to use a backlit button panel that was glowing very nicely. It turned out that it would have been really expensive. Plus, there were no Indian suppliers that could support us. So we*

had to adapt the design to what was available on the market. This is why you see some empty space here." (Mid-level manager - Styling)

5.3.2 Using software as sub-system integration tool

From a technological perspective, Mahindra Reva's ex-post integration efforts were supported by the highly flexible Intelligent Energy Management System (IEMS), which allowed the company to successfully integrate the EV-specific components. As mentioned above, the electrical architecture of EVs consisted of 'hardware' components, such as the battery pack, the engine, the controller, or the charger. This hardware structure was operated and controlled through the IEMS software. While the 'hardware' was produced by independent suppliers, which following the knowledge transfers from Mahindra Reva had become able to provide components suitable for various applications ranging from small four-sitter vehicles to trucks and vans, the IEMS 'software' represented one of Mahindra Reva's main competitive advantages and a critical integrative tool:

> *"The IEMS works with different types of batteries [e.g. lead-acid or Li-ion]. It requires minor code changes, but it is structured to accommodate numerous variations. This is very important for us because our models use different batteries, different voltages, different numbers of cells. Plus, the chemistries are constantly changing. We need to be able to adapt to anything. This is the philosophy of our design."* (Mid-level manager – New Technologies and IP)

and

> *"We developed our internal capability to adjust the software of the IEMS. This software does a lot of things within the vehicle. It interacts with the majority of the electronic parts such as the charger, motor controller or the instrument cluster. […] The software is very flexible and can be easily upgraded. For example, if the marketing department wants to add some feature we can do it through the IEMS. Such additions or adjustments can be*

done almost without costs, no tooling costs, no hardware costs, no time to impact. We make the code changes, validate them properly and go for the implementation." (Senior manager – R&D)

Thus, the IEMS was critical for Mahindra Reva's modular electric architecture. The software not only opened opportunities for outsourcing (Baldwin & Clark, 2000), but also supported directional, trial-and-error solution searches involving a wide range of 'hardware' configurations (see Nickerson & Zenger, 2004).

6. DISCUSSION AND CONCLUSION

6.1 Theoretical contributions

Despite the academic and practical importance of studying open innovation at the project level (Du et al., 2014; Felin & Zenger, 2014), previous research on open innovation has been mainly conducted at the firm level (Antons et al., 2016; Randhawa et al., 2016). Switching the level of analysis from the firm level to the project level, this paper provides empirical insights about the relationship between project complexity and open innovation in the B2B context. Thus, we address the recent calls to conduct project-level studies in open innovation management (Antons et al., 2016; West & Bogers, 2017).

In addition, by exploring the relationship between project complexity and open innovation, our study empirically builds on the problem-solving and product design perspectives. These two perspectives consistently argue that involving business partners in innovation projects may not be appropriate when addressing complex problems, mainly due to: (1) the difficulty of integrating highly interdependent sub-systems developed by independent third parties (Fujimoto, 2007); and (2) the potential knowledge leakages to business partners caused by the extensive knowledge sharing between the partnering firms that is required for solving complex problems (Felin & Zenger, 2014; Nickerson & Zenger, 2004). However, practice shows that some organizations do rely on open innovation with business partners to solve complex innovation problems (e.g., Brunswicker et al., 2016; Morris, 2017; Tang et al., 2009). These organizations seem to prioritize the benefits that open innovation can bring (e.g., access to rare resources and complementary capabilities, cost reductions, and time to market) over the risk of potential knowledge leakages to organizational outsiders and system integration difficulties. Considering such risk and difficulties, our study aimed at exploring and understanding how firms can manage extensive collaborations with their business partners (i.e., B2B open innovation) for delivering commercially viable complex innovations.

On one hand, our findings contribute to the product design literature (Fujimoto, 2007) by showing that the challenge of incompatible or misaligning sub-system and component designs performed by business partners can be managed via a carefully planned, multi-stage process of system integration. More precisely, in an early design and development stage, relying on hierarchical architecture can pave the way for decomposing complex projects. This hierarchical architecture enables the company to divide the overall system (i.e., the product) into sub-systems and components corresponding to knowledge domains and capabilities of potential business partners. In addition, having a flexible system design can help reduce the negative impact of future misalignments in the design and development of sub-systems and components. In the next stage of design and development, sub-system co-development involving the focal firm and external business partners can facilitate communication and knowledge sharing regarding sub-systems and components, interface requirements, capabilities, and production lines. Thus, co-development can preempt design misalignments, while contributing to cost and time reductions. Lastly, we find that ex-post system integration is contingent not only on the focal firm's design alignment and integration capabilities, but also on the extent and efficacy of the ex-ante integration and co-development efforts. To the best of our knowledge, this is one of the rare empirical papers in the open innovation literature exploring the activities and practices entailed by system integration in complex innovation projects.

On the other hand, our findings contribute to the problem-solving literature (Felin & Zenger, 2014; Nickerson & Zenger, 2004) in two ways. First, we show that, in early stages of a technology trajectory, the hazard of knowledge leakages due to opportunistic behavior of business partners is not a key barrier preventing firms from engaging in open innovation for complex projects (see also Alexy et al., 2013). Even though the problem-solving literature argues that "opportunism in knowledge exchange discourages actors from sharing knowledge" (Nickerson & Zenger, 2004, p. 622), we show that firms actually engage in selective knowledge sharing, which involves sharing specific parts of the knowledge with external partners, in the early stages of the technology trajectory. Our findings are also echoing Tesla's 2014 decision to release all EV-related patents "in the spirit of the open source movement." At the time of Tesla's patent release, the then-CEO Elon Musk explained that "if we clear a path to the creation of compelling EVs, but then lay intellectual property landmines behind us to inhibit others, we are acting in a manner contrary to that goal".[1] Second, even though the literature on inter-organizational knowledge sharing argues about the difficulties of knowledge exchange across organizational boundaries, tacit knowledge in particular (Felin & Zenger, 2014; Nonaka, 1994), we show that such difficulties can be mitigated through practices supporting sub-system and component co-development, such as deputing staff from one business partner to another and collaborating with proximity-located business partners.

6.2 Managerial implications

Apart from its theoretical contributions, our study also has some implications for managers deciding how to manage their company's innovation processes. Our study indicates that managers dealing with complex innovation projects should embrace open innovation, despite the risk of potential knowledge leakages to organizational outsiders and system integration difficulties that open innovation implies. To minimize this risk and difficulties, managers

[1] https://www.tesla.com/blog/all-our-patent-are-belong-you, retrieved in June 2019.

should consider implementing system integration in three stages: (1) ex-ante integration; (2) co-development; and (3) ex-post integration.

While ex-post integration is a practice widely spread across industries, we suggest that managers should consider potential integration problems ex-ante, as this may reduce the duration, cost and difficulty of the ex-post integration. Moreover, a hierarchical product architecture can help managers decompose complex innovation projects into sub-systems and components, whose design and development can be outsourced to knowledgeable external business partners. In addition, managers should bear in mind that flexible designs that can be modified easily at later stages may also reduce the cost of ex-post integration. Similarly, co-developing the main sub-system with external partners can prevent design and interface misalignments.

6.3 Limitations and future research

This paper has several limitations and raises some future research opportunities. First, although Mahindra Reva was a pioneer in the EV segment, it consistently faced resource constraints that contributed to the company's proclivity toward open innovation. In that sense, according to our informants, "if we did not collaborate, we would not have our EVs" (CEO). Therefore, future studies could investigate if resource constraints are a key driver of the adoption of open innovation in complex innovation projects or if resource-constrained and munificent firms alike choose to open up complex projects to the outside world due to cost and time-to-market benefits.

Second, although we showed that developing EVs is a complex project, other innovation projects can entail higher complexity levels than EVs. For example, the Boeing's 787 Dreamliner aircraft was a highly complex project that was subject to open innovation. Boeing relied on approximately 50 first-tier strategic partners that provided original designs for critical sub-systems and pre-integrated the designs of second-tier partners (Tang et al., 2009). However, due to the high project complexity and novelty, Boeing faced major system integration problems that delayed the launch of the aircraft by several years (Chesbrough, 2011). Thus, future research could investigate the relationship between the level of project complexity and the importance and difficulty of system integration.

Third, our case study focused on EVs, which are at an early stage of the technological trajectory, still far from maturity. The immense market potential and the absence of industry-wide technology standards have influenced Mahindra Reva's limited concerns regarding knowledge leakage hazards. Thus, future research could investigate whether and to what extent firms' attitudes toward knowledge sharing are different in more mature industries and saturated markets.

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8. TABLES AND FIGURES

Table 1. Component – functionality correspondence in Mahindra Reva EVs

Component \ Function	Top Speed	Driving Range	Vehicle Control	Passenger Safety	Aesthetics
Battery	●	●			●
Motor	●	●	●		
Plastic External Body	●	●		●	●
Tubular Frame (Chassis)				●	●
IEMS	●	●	●		
Regenerative Brakes		●	●	●	

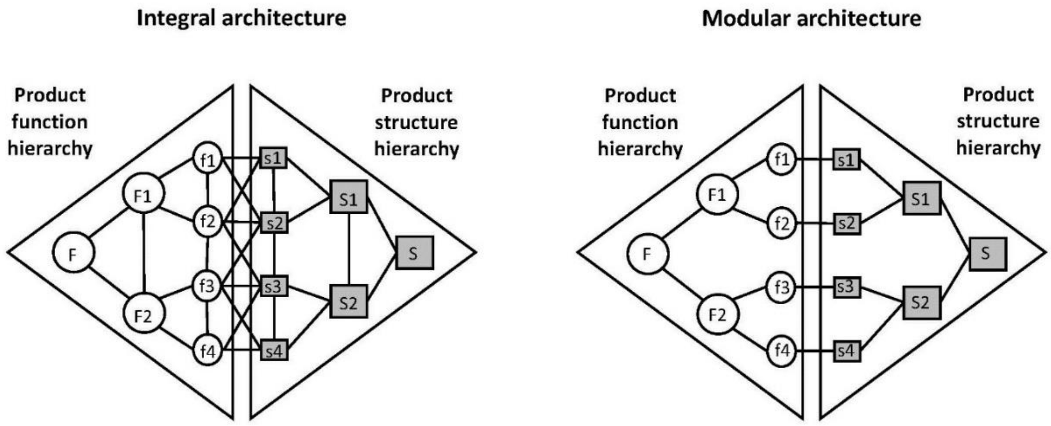
Table 2. Interviews

Hierarchical levels of informants	Number of interviews
CEO	1
Senior managers	11
Mid-level managers	14
Front-line employees	22

Table 3. Main sub-systems in the hierarchical architecture of EVs

Component/ Sub-system	Supplier/Partnership
Charger	The EV chargers were developed through a collaboration involving Mahindra Reva and US-based company specializing in high technology power conversion products for defense and aerospace sectors. Currently, the chargers for Mahindra Reva's EV are produced by local supplier.
Lead-acid battery packs	The first lead-acid batteries were co-developed with a UK-based supplier. The original supplier was later replaced by an Indian partner.
Li-ion battery packs	The Li-ion battery cells were developed and produced by a Chinese company specializing in batteries for small portable devices.
Motor controller	The controllers were developed by Mahindra Reva in collaboration with a US company specializing in battery measurement equipment.
Motor	The EV motors were developed by Mahindra Reva in collaboration with a leading Indian electrical engineering company.
Plastic body panels	The ABS panels were developed by Mahindra Reva in collaboration with two Indian plastics manufacturing.
Tubular spaceframe chassis	The spaceframe chassis were developed by Mahindra Reva in collaboration with a local supplier.

Figure 1. Modular and integral architectures



Legend: F= product function as a whole, S= product structure as a whole; F1, F2= product sub-functions; S1, S2= large modules; f1-f4= product sub-sub-functions; s1-s4= small modules

Source: Fujimoto (2007).