Automotive in Transition

Challenges for Strategy and Policy

edited by Andrea Stocchetti, Giulia Trombini, Francesco Zirpoli

Edizioni
Ca'Foscari

Università Ca’ Foscari Venezia
Dorsoduro 1686
30123 Venezia

edizionicafoscari.unive.it

ISBN 978-88-97735-37-3

3

The impact of electric motorizations on car architecture and supply chain relationships within the automotive industry

Anna Cabigiosu

1 Introduction

This chapter addresses the issue of electric vehicles (EVs) architectural changes and then, building on the modularity literature, debates the implications of their supply chain management. In fact, there is still no study that a) reviews the existing contributes about EVs' architectural changes and helps appreciating whether EVs are moving, and to what extent, toward higher levels of modularity, and that b) relying on the modularity literature discusses their managerial implications.

J.P. Morgan estimated that by 2020 about 11 millions of EVs will be sold worldwide («Automotive News» 2009). According to J.P. Morgan, this will mean that EVs will equal nearly the 13% of the global passenger market at that point in time.

Interestingly, following both the managerial and engineering literature, electric motorizations will affect car design and architecture and, in turn, the way in which carmakers manage design activities and the corresponding supply relationships. Particularly, some scholars have argued that EVs will migrate towards more modular architectures that may lower the need of hand-in-glove relationships between carmakers and suppliers (MacDuffie 2012; Christensen 2011).

The modularity literature suggests that, beside EVs, many products are becoming more modular over time, and that this development is often associated with a change in industry structure driven by the quest for the benefits provided by higher degrees of specialization and disintegration, as the PC industry illustrates (van Bree et al. 2010; Baldwin, Clark 2000; Fine 1998; Fixson, Park 2008; Langlois 2003). In the specific case of the car industry the growing interest in the modularization of design is also determined by the strategic focus on the product architecture (Batchelor 2006). It is reasonable to assume that such interest will be intensified in view of the expected renewal of the dominant car design.

Within this area of research, studies have investigated the relationship between the degree of product modularity and the nature of vertical inter-firm relationships, namely the across firm «mirroring» hypothesis (i.e. if and to what extent products and organizations share similar architectural properties and, more specifically, if and to what extent the degree of modularity of sourced components is inversely related to the «thickness» of buyer-supplier relationships) (Cabigiosu, Camuffo 2012). While the «mirroring» hypothesis finds support in the 70% of the studies (Colfer, Baldwin 2010), the automotive industry appears to be a special case in that a) cars today are still overall integral products (MacDuffie 2012) and b) there is no conclusive answer to key questions concerning the role of modularity in shaping the vertical contracting structure and inter-firm coordination of the car industry (Cabigiosu, Camuffo, Zirpoli 2013; Zirpoli, Becker 2011).

While modularity in production and platforms design are already widespread practices in this industry, till now modularity in design has been confined to subsystems such as the A/C system and the automotive console (Fixson 2003; Sturgeon, Lexter 2003). Carmakers mainly leverage on product platforms that include components shared among a variety of car models, but only a few of them are modular.

In this scenario, scholars suggest that also EVs are designed and produced relying on platforms but even that new electric technologies are increasing the cars' modularity level (Christensen 2011).

As MacDuffie (2012) suggests, product architecture of new electric vehicles needs to accommodate heavy battery packs, a high-capacity electrical system, complex software, and small electric motors potentially located in the wheels. Indeed, mapping from function to component is likely to move closer to the one-to-one correspondence that is found in electronic and information technology products. Moreover, today a large number of components used in the various electric drivetrain solutions are shared. Hybrid drivetrain, the fuel cell drivetrain and the battery electric drivetrain all share components and systems such as batteries, electric motors, inverters, generators and brake energy regeneration systems (Christensen 2011). All in all, components commonality across different electric and hybrid motorizations may facilitate modularity-in-design and shift the industry's definition of module away from modularity-in-production. Particularly, modularity-in-design may support «the rise of new suppliers providing specialized expertise for module design and production, and change the prevailing division of labour between OEMs and suppliers» (MacDuffie 2012, p. 49).

The chapter is structured as follows. The first section clarifies the concept of modularity in products and in organizations, while the second synthesizes the main findings about modularity and platforms in the automotive industry. The third paragraph describes the main car architectural changes identified/forecasted due to the introduction of new electric motorizations. The fourth section reviews the modularity literature and identifies those key car attributes (e.g. the car complexity), industry specificities (e.g. the rate of technological change), and carmaker strategies (e.g. the level of vertical integration and knowledge endowment) that all may help in predicting whether and to what extent EVs higher modularity level will reshape supply relationships. The conclusion section draws the research and managerial implications and points out some future research directions.

2 Modularity in product design and in organizations

The scheme by which the functions of a product are allocated to its components is called its «architecture» (Ulrich 1995). Modularity refers to the way in which the design of a product is decomposed into different parts or modules that are characterized by independence across and interdependence within their defined boundaries (Campagnolo, Camuffo 2010; Ulrich 1995). This independence is achievable through the adoption of standard interfaces that decouple the development and the inner working principles of a product's components (Baldwin, Clark 2000). Despite the differences in approaches, scholars converge in identifying three main features of modules: they are separable from the rest of the product; they are isolable as self-contained, semiautonomous chunks; and they are re-combinable with other components. Separability, isolability, and re-combinability are properties deriving from the way functions are mapped onto the components and from how components interact, i.e. from their interfaces.

Ideally, a perfectly modular product is made of components that perform entirely one or few functions (1:1 component/function mapping), with well-known, defined and codified interfaces among them (Ulrich 1995). If these interfaces – i.e. the communication protocols among components – are widely diffused within a given industry, these components have open standard interfaces. However, if the protocols are designed specifically to suit a certain firm's requirements, i.e. they are firm specific, these protocols are closed and non-standard, unless we consider closed interfaces as proprietary standards used by a single firm or a specific network of firms (Fine et al. 2005). Interestingly, modular products are characterized by standard interfaces among components, but the other product's features and attributes – including technologies – may change. Thus, a modular component is not necessarily standard.

Research on the degrees of coupling between product and organizational architectures has flourished during the last two decades. Within this body of research, some studies recently investigated the relationship between the degree of product modularity and the nature of vertical interorganizational relationships (Baldwin, Clark 1997, 2000; Fixson, Park 2008; Colfer, Baldwin 2010).

In the extreme case of full product modularity, all the components exclusively perform one or few functions and the interfaces among them are completely open standard. In this case, all the suppliers that design and produce a given component use the same interfaces or a closed set of interfaces. Thus, they do not need to discuss with the buyer how components should be designed in order to fit the product design. Since components' design and development can be isolated and conducted separately by suppliers within a «frozen» product architecture, co-development practices are unnecessary and the advantages of relational quasi-rents negligible. Buyers and suppliers need not to engage in «thick» relationships through which continuously improve products and processes, control opportunism, and share risk.

In 1996, Sanchez and Mahoney formulated the «mirroring» hypothesis suggesting that loosely coupled standardized interfaces in a modular product architecture provide a form of coordination that reduces the need for overt exercise of managerial authority to achieve coordination of development processes. In such cases, the concurrent and autonomous development of components by loosely coupled organization structures is possible. Modularity in product design reduces the need for «hand-in-glove» supply relationships, because knowledge encapsulation within modules lowers inter-firm interdependence and, hence, coordination and control needs (Sanchez, Mahoney 1996; Langlois 2003). The suppliers that design and produce modular components know ex ante the interfaces of the component; this, in turn, reduces the information exchanges needed to design a component that fits the overall product design. Since component design and development can thus be isolated and carried out separately by suppliers within a «frozen» product architecture, the need for intense coordination is lowered. Also, modularity in design can improve the management and the outputs of the new product development activities by allowing firms to easily decouple both the design and the manufacturing of the components that constitute a product as well as ensuring an easy and well performing integration of the externally supplied components into the final product architecture.

Overall, modularity in design should lead to modular supply chains in which members have few close organizational ties and, thus, may be more easily mixed and matched, highly dispersed and geographically and culturally distant (Fine 1998; Doran 2007). According to Sturgeon (2002), a modular industry is fragmented owing to various specialized capabilities associated with the manufacturing of various components. A modular industry is characterized by loose coupling of component designs, and a loosely coupled knowledge, a high rate of innovation, designers flexibility in developing and testing products, and a high number of compatible suppliers.

In the modular networks, the overall industry structure remains vertically disintegrated. While some OEMs retain internal manufacturing capacity for specific reasons (fear of intellectual property loss, tight integration between processes and product innovation, retention of process expertise to qualify outsourcing partners, etc.), globally operating contract manufacturers facilitate the build-up of external economies of scale and scope. Sturgeon (2002) calls this model modular production network «because distinct breaks in the value chain tend to form at points where information regarding product specifications can be highly formalized». Between these nodes, linkages are achieved by the transfer of codified information. The author underlines how such a network is allowed by standards consolidation inside an industry that works as communication protocols. Components with standardized and industry-wide accepted interface specifications decouple firms from one another, leading to increased specialization and technological improvement of components independently from innovations of other firms (Mikkola 2003). Moreover, inside modular networks the trust, one of the features of the local networks, is substituted by international standards, which permit to compare different suppliers on a common base. Firms, by outsourcing a large share of their manufacturing, become more organizationally and geographically flexible. Being the suppliers' production relatively flexible in terms of volumes and products characteristics, their transactions with brand-name companies remain general. Instead of «thickly relational» interactions between firms, as in the relational networks, modular supply chain are characterised by «thinly relational» interactions because the supplier specifies its own processes, purchases its own inputs, and retains an autonomous financial stance vis-à-vis its customer (Sturgeon 2002). Indeed, modular networks are characterised by the limited interdependence among actors. Thus autonomy is based on several preconditions as the use of IT, «base processes», and widely accepted standards. All in all, modular supply chains are more flexible and eventually global.

Interestingly, in reviewing the literature Colfer and Baldwin (2010) found that the mirroring is supported in the 70% of the cases and it is positively correlated with the firm's performance. Nevertheless, while the modularity literature emphasizes the existence of the mirroring as well as its performance implications, most recent contributes identified the necessity to build a contingent view of this theory.

Particularly, Cabigiosu and Camuffo (2012) identified some conditions under which the mirroring holds, such as (a) the stability of product architecture; (b) the presence of industry standards; (c) firms' strategies, organizations, and capabilities not aimed at increasing the integration with suppliers. Moreover, Furlan, Cabigiosu and Camuffo (2010) highlighted that, even for highly modular products with a stable product architecture, we are less likely to observe the «mirroring» in technologically dynamic industries, characterised by incremental and modular innovations, where buyer-supplier integration is needed no matter the level of component modularity. Zirpoli and Becker (2011) show that component modularity does not substitute for high powered inter-organizational mechanisms, in the sense that it does not solve the problem of integrating component's technical performance within the vehicle. Defining standardized physical interfaces does not standardize the performance contribution of a component and does not reduce the reciprocal interdependencies between component and vehicle performances. The authors show that this is particularly true for complex and technologically dynamic components (such as electronics or car occupant safety systems). Brusoni et al. (2001) show that, when the architecture of fast changing components stabilizes, manufacturers outsource both design and production but keep in house component-specific knowledge for rapidly changing components whose dynamism generates the possibility for technological unbalances.

In this study, we will rely on the above literature to discuss if, how and to what extent EVs' architectural changes may affect supply relationships management practices.

3 Modularity in design in the automotive industry

The past decades have shown an increase in vehicle development and manufacturing outsourcing with a consequent shift in tasks and knowledge from carmakers to first-tier suppliers. Nowadays the key processes own by the carmakers have a narrow focus: vehicle design and engineering, manufacturing of chassis, body, engine and powertrain, final assembly. All other components (interiors, cockpit, braking system, electrical system, traction control system, fuelling system, exhaust system, coolant system) are usually designed, engineered and manufactured by suppliers (Takeishi 2001; Fixson et al. 2005).

In this context, modularity has attracted the interest of scholars in that early studies showed that product modularity reduces the need for a tight coordination between buyer and supplier during the product development stage (Doran 2004; Fixson et al. 2005; Ro et al. 2007): the specifications of standardized component interfaces and a clear one-to-one component-function mapping were credited to create an information structure that allows coordinating the activities as loosely coupled. Moreover, component modularity should increase and ease the rate of introduction of modular and incremental innovations while the concurrent and autonomous development of components speeds the throughput time of NPD activities thus reducing the NPD costs (McDuffie 2012).

Despite the expected benefits of modularity in design, recent empirical evidence shows that only few car components at the first level of the product hierarchy are truly modular and cars are overall integral products: the modularization efforts of some US and European carmakers have not been implemented successfully, with rare exceptions (Ro et al. 2007; Sako 2003). In this respect, Fixson (2003) reviewed existing literature about product modularity in the car industry and offered a list of vehicle sub-systems that the literature has classified as modular. These systems are located at the first level of the vehicle product architecture hierarchy and are: the A/C system, the automotive console, the underbody, the instrument panel, the brake system, and the climate control.

Overall, only few car subsystems are highly modular. Recent studies suggest that while modularity may enhance carmakers' performance, modular strategies are not *the most* performing in this industry and that further modularization processes in the A/C system would not necessarily lead to inter-organizational loosely coupled relationships between OEMs and suppliers (Cabigiosu, Camuffo, Zirpoli 2013; Zirpoli, Becker 2011). Cabigiosu et al. (2013) show that the complexity in the car architecture reduces the chances of modularity to be effective as a functional equivalent of high-powered inter-firm coordination mechanisms (Cabigiosu, Camuffo 2012; MacDuffie 2012; Zirpoli, Becker 2011). High-powered inter-organizational coordination mechanisms remain necessary to ensure effective and efficient product development. Moreover, they show that, in order to increase the modularization of vehicle components, carmakers need to heavily invest in component-specific knowledge (i.e. increase their level of vertical integration) and that the knowledge they held, more than component modularity, enhances the coordination with suppliers. One exception is identified by MacDuffie (2012) that describes the case of Chinese carmakers. These OEMs design modular cars because they almost completely rely on external suppliers to design the car systems. Once the suppliers have designed the car systems, the Chinese OEMs preserve these architectures that, otherwise, they would not be able to fully manage.

Overall, modularity has still a limited traction in the automotive industry and the evidence about its impact on supply chain management is not decisive. In the automotive industry we mainly observed that modularity in production is defined as the outsourcing of a product's components: independent companies (e.g. suppliers) may develop, produce and deliver subsystems that are consistent with the scope and depth of their core competences (Campagnolo, Camuffo 2010). Modular designs are supposed to ease modular productions. While modularity in organization relates to how supply chain relationships are managed, modularity in production attains to the disaggregation of the production activities along the supply chain. Today, the automotive industry shows a high level of modularity in production and a low level of modularity in product design and organization, i.e. cars are overall integral products while subsystems are externally sourced maintaining a high level of integration with suppliers.

By reviewing the existent literature, this paper aims at evaluating the expected level of modularity of EVs and, by building on the modularity theory, at discussing how EVs' architecture may affect the management of supply chain relationships.

4 Electric vehicles main architectural changes

This study focuses on EV's main architectural innovations and their organizational implications with a focus on supply chain management strategies. Particularly, in this section we will review the existing literature on EVs to understand if and till what extent EVs are, and are likely to become, more modular in their design.

EVs powertrain system mainly consists of an electric engine that moves the wheels, a battery for energy storage, and an electronic control system. Initially, most car manufacturers, such as Renault and Peugeot, favored electrifying existing models pursuing a low-cost strategy. These EVs were unsuccessful, mainly due to limited range, and a higher price relative to comparable IC vehicles. After 1997 a few car makers, such as Toyota and Honda, launched hybrid vehicles that have similar range as IC vehicles. By 2008, the US market shares of these models growth till 4% (Dijk, Yarmine 2010), The first generation of EVs is derived from the adaptation of existing product platforms. Presently, electric vehicles are, with very few exceptions, obtained through the adaptation of chassis (or floor pan), bodies and powertrain engineered for traditional internal combustion engines (IC). Also hybrids and fuel cell solutions can often be integrated into existing vehicles with minor changes to the car's design.

Consequently, EVs, hybrids and fuel cell cars all suffer from under-optimized energy efficiency and car's architectures. The perspective of very low sales volumes and the dramatic uncertainty about the future of EVs technological trajectories has refrained so far carmakers from heavily investing into dedicated EVs' architectures for the mass market. Moreover, battery and fuel cell technology are likely to be niche markets because batteries are still comparatively expensive components. Broad diffusion for EVs is expected only around 2020 (Brown et al. 2010). Consequently, today EVs are often built on IC-based platforms and only the second generation of EVs may go over this technological lock-in (Cowan, Hultén 1996; Midler, Beaume 2010). Marletto (2011) talks about a «car regime» environment in which the lock-in is so much rooted that shift towards ecological motorization could be achieved only through policies of institutional change. Van den Hoed (2007), studying patents in alternative drivetrain technologies, showed that manufacturers invested in both battery electric drivetrains and hybrids and fuel cell solutions but gave priority to the latter because they can more easily lead the drivetrain electrification in mass-produced cars.

Table 1 shows that today the main components that are *not* in common between IC cars and EVs are those belonging to the engine group and the transmissions (Cuenca et al. 1999). Indeed, we will now focus on how the architecture of these components is changed and till what extent they may affect the overall car's architecture and its modularity level.

According to Christensen (2011), a large number of the components, such as batteries, electric motors, inverters, generators and brake energy regeneration systems, are shared across EV, hybrid and fuel cell drivetrain solutions. The similarities of alternative drivetrain technologies suggest that their development activities can be partially shared and that the drivetrain can become more modular. Christensen (2011) provided some examples of how alternative drivetrain technologies are affecting cars' architecture. General Motors developed the GM Hy-wire model following a platform approach in which a skateboard-like lower body, containing a full fuel cell system with drive-by-wire technology, can be applied to various upper body vehicle applications. The Chevy Volt, produced by General Motors, has an electric drivetrain developed on a platform that facilitates the flexible choice between three different propulsion options: a pure battery electric option, a combined electric/combustion engine option and a combined electric/fuel cell option. In such a case, the three propulsion options constitute three modules. Finally, Mitsubishi has developed a design strategy where «the modularization of related components for electric drivetrains enables the company to develop components for three interchangeable drive systems simultaneously. Mitsubishi has designed an in-wheel assembled electric engine that can be applied to a battery electric vehicle, a hybrid electric vehicle or a fuel cell electric vehicle» (p. 217). The lithium-ion battery and the in-wheel electric motor are both produced by external suppliers.

These cases suggest that both the engine and transmission can be designed as car's modules and have an inner modular architecture which components can be shared across platforms. Moreover, following Christens (2011), EV concepts will improve the feasibility and implementation of the drive-by-wire (DBW) technologies that eliminate the mechanical connection between the steering wheel and the steering gear box thus freeing up space in the engine compartment. A small motor aids the driver to turn the steering wheel in a smooth easy motion. Instead of operating the steering and brakes directly, the controls would send commands to a central computer, which would instruct the car what to do. The great advantage being put forward for this is that it would possible to improve the roadholding and of the overall energy efficiency through the electronic control of the joint work of steering, suspensions and brakes in response to driver's actions and road conditions (Varghesee et al. 2008).

DBW would provide a triple source of benefits: i) gear lever, steering columns and pedals could be abandoned with benefits in terms of lower complexity, weight and space thus increasing the degree of freedom in the interiors design; ii) making the chassis and the body independent with a DBW solution would give the possibility to design and engineer these two macro-components separately, theoretically as two separated modules. Indeed, the elimination of mechanical elements for driving control is a premise for a radical detach of the chassis (which would include all elements needed to assure the motion: engines, transmission, batteries, brakes and so on in a sort of «surfboard») from the body and the passengers' cabin (presently chassis and the body are welded together). The potential advantage is to have a lower number of interfaces, a much higher freedom of design of the body and the interiors coupled with a higher degree of standardization of the surfboard. As Cabigiosu et al. (2013) suggested, highly modular cars are characterized by a wide reliance on open-standard interfaces that can constraint the car's style viable options. The overall reduction of EV complexity is key to avoid

Table 1: components in common between IC vehicles and EV.

Vehicle group and subgroup	Fully common	Somewhat common	Not common
Body group			
Body-in-white	×		
Paint and coatings	×		
Glass	×		
Interior body trim	×		
Exterior body trim	×		
Seats	×		
Instruments panel		×	
Restraint system	×		
Body electrical components	×		
Heating, ventilating, and air-conditioning (HVAC)		×	
Engine group			
Base engine			×
Emission control			×
Engine accessories			×
Engine electrical components			×
Cooling system			×
Transmission group			
Transaxle			×
Clutch and actuator			×
Transmission control			×
Chassis group			
Frame	×		
Suspension	×		
Steering		×	
Brakes		×	
Exhaust system			×
Fuel storage			×
Final drive	×		
Wheels and tires	×		
Bumpers, fenders, and shields	×		
Chassis electrical components		×	
Accessories and tools	×		
Fluids		×	

Source: Cuenca et al. 1999, p. 10.

that too many frozen interfaces limit OEM's design choices; iii) finally, the substitution of mechanical interfaces with electrical ones and the opportunities offered by the integrated electronic control of the whole powertrain should ease the development of open standard interfaces.

EVs have no emission (therefore no exhaust system is needed) and can exploit the advantages of direct transmission. Theoretically, no clutch or conventional gearbox are needed, since the electric engine provides a very high torque since the minimum regimes. Differential can be eliminated connecting electric motors to the wheel axle. Since all transmissions elements are a major source of lost in efficiency, designer will likely tend to focus on solutions that eliminate them (Larminie, Lowry 2003; Kulkarni et al. 2011). The «extreme» solution is to have the motors coupled to the wheel-shaft; such a solution provide a significant improvement in performances (speed and acceleration) and a very significant saving in space and weight.

Also, EVs allow partially substituting mechanical interfaces with electronic interfaces. In traditional cars a huge shares of electronic systems are devoted to the control of IC functioning (injection, fault diagnostic, cooling, etc.). Such systems will disappear while driving and traction controls electronics will probably became even more relevant and, as suggested by the history of the PC industry, they are likely to become open standard interfaces (Baldwin, Clark 2000). As concern this last point, there already exist industry standards for computers, batteries and battery components. Nevertheless, there is still a need to develop international standards for larger-scale battery packs that can be used by the EV as well as advanced and future battery technologies. «Basic standards and frameworks exist, but much work to bring the needed regulations and standards to light is still required. A number of the most pressing areas have been identified, particularly new battery technologies, the emergence of V2G (vehicle to greed) technologies and possible impacts on the quality of electricity on power networks, and in terms of the full lifecycle environmental impacts associated with the EVs» (Brown et al. 2010, p. 3806).

Overall, EVs allow reducing the number of car's components, the interfaces among them and partially substituting mechanical interfaces with electrical interfaces that are easier to standardize. Today, these architectural changes mainly regard the engine group and the transmissions that are still «plugged in» a traditional IC based vehicle thus reducing the potential EV efficiency.

To achieve EV «product integrity», as defined by Clark and Fujimoto (1990), OEMs may need to deeply revise the next generations of EVs' product architectures to adapt to new constraints (especially the battery location). They need to rethink the performance criteria, which drive the technical design choices on nearly every component of a car. For example, energy efficiency is a key performance for EVs as it has an immediate impact on vehicle autonomy. Thus, redesigning more energy efficient lighting or heating is a key aspect of future EV projects. The whole design system has thus to be reoriented on the new electric mobility paradigm. The occurrence of a «performance gap» may be satisfied only by more technically integrated solutions (Brown et al. 2010; Sierzchula et al. 2012).

5 EVs, modularity in design and supply chain relationships

In this section we debate, building on the modularity and the innovation management literature, what will be the expected effects of a EVs' architecture on supply chain management relationships. First, we will discuss the role that the interplay between modularity and technological dynamism has in shaping supply relationships. Second, we will include into the analysis OEMs organization, strategies and capabilities.

The literature suggest that often industries become disintegrated over time (Baldwin, Clark 2000). As Fine and Parker outline (2008), this disintegration has been explained by the increasing efficiency through the division of labor and, at the firm-level explanation, by the potential gains from specialization and gains from trade. In their work on the evolution of the computer industry, Baldwin and Clark (2000) describe the initial creation of the modular architecture as preceding the emergence of a modular industry structure. Also Glavin and Morkel (2001) and Fixson and Park (2008) emphasized the relationship between product architecture and supply chain management practices in the bicycle industry.

The above analysis suggests that OEMs' attempts to move toward higher levels of modularity may be eased by electrification (Christensen 2011). The observed higher modularity levels may support the idea that these architectural changes may enhance more loosely coupled supply relationships, increasing the suppliers substitutability, easing the integration of external sources of innovation till eventually leading to modular supply chains (MacDuffie 2012; Sturgeon 2002).

The analyzed EV's architectural characteristics, such as the EV's lower number of interfaces and components, suggest that EVs are, other things equal, more modular than IC vehicles and that EVs may potentially reduce the complexity of the design activities and of the corresponding supply relationships.

Moreover, the need to contemporarily plug-in EV, hybrid and fuel cell drivetrain solutions into IC car's platforms may foster the development of shared standard interfaces, ease the integration of externally sourced components and reduce the need of hand-in-glove relationships with suppliers.

Besides, the above paragraphs also describe how today EVs do not only display architectural changes but also embody innovative technologies, as the DBW technology. Moreover, both EVs' architecture and technologies are likely to face further modifications in the next years. Indeed, the potential managerial implications of EVs' higher modularity level should be discussed contingently on the level of technological change of the first generation of EVs as well as on the future technological trajectories that may regard EVs' technologies and dedicated platforms.

Cabigiosu and Camuffo (2012) suggest that modularity in products and organizations may be related only if product architecture is stable. Component modularity works as a functional equivalent of high-powered inter-organizational coordination mechanisms only if the product architecture is ex-ante defined and frozen thus embodying those open and widely diffused standard interfaces that ease the coordination between a buyer and a supplier.

Nevertheless, even if the product architecture is stable, we may not observe a relationship between modularity in products and in organizations. When the product architecture is stable we may still observe intense and frequent modular and incremental innovations. In industries characterized by high levels of incremental and modular innovations, buyers may remain interested in getting access to supplier's knowledge base, in monitoring suppliers' cost structures and performance via collaborative and «thick» supply relationships (Furlan et al. 2010). As Wolter and Veloso (2008) suggest, when component technological change is frequent, buyers will engage suppliers in an intense information and knowledge sharing and will rely on complex integration and control mechanisms, no matter what the degree of modularity of the sourced components is. In general, technological variation in components continuously generates inter-organizational interdependencies throughout the product development process, despite efforts to limit them through modularity.

Thus, till EVs will be characterized by architectural changes and/or by frequent and intense modular and incremental innovations, even if the car's architecture is modular, we cannot expect that their supply chain will become modular *à la* Sturgeon (2002).

When OEMs act as system integrators of complex and technologically dynamic components, such as cars' subsystems, they have to keep substantial component specific knowledge even about outsourced components. Two ways to nurture this component specific knowledge are to maintain a high level of vertical integration or to remain engaged in «thick» relationships with suppliers. Brusoni et al. (2001) show that manufacturers keep in house component specific knowledge for rapidly changing components. OEMs acquire component specific knowledge to maintain the ability to act as system integrators and develop collaborative relationships with suppliers. Cabigiosu et al. (2013) show that the ability to design a highly modular car's subsystem is contingent upon an in-depth knowledge of both the subsystem architecture and its inner components. Given cars' architectural complexity, only OEMs with components specific knowledge can design more modular systems and experience the benefits of this architecture, as coordination and control mechanism. While component modularity and design outsourcing are considered as complements in modularity literature, they may be difficult to combine. Carmakers can effectively modularize a system if they maintain in-house some subsystems specific knowledge increasing their level of vertical integration or, alternatively, if they extensively rely on supplier's competences and high-powered integration mechanisms.

On the transactions point of view, tapping into the capabilities of the supplier by continuously exchanging information about the product or the process allows the buyer to better evaluate of supplier's offers. Moreover, technological change increases the performance uncertainty of the sourced components and makes it more difficult for the buyer to develop measures of suppliers' performance. Therefore, the partners need to share information and maintain collaborative hand-in-glove supply relationships to reduce information asymmetries and to write clear and credible contracts, no matter what is the level of component modularity (Furlan et al. 2010; Wolter, Veloso 2008).

Therefore, despite the EVs' potential higher level of modularity, we do not expect that modularity may substitute high-powered integration tolls till EVs will face architectural changes and/or frequent and intense incremental/modular innovations: supply chain relationships are likely to remain collaborative, characterized by an intense information sharing and physical co-location. On the contrary, if EVs' architecture will stabilize *and* innovations will be characterized by a low frequency and intensity, modularity in design may ease the management of supply chain relationships.

Besides, even under these circumstances, organizational interdependencies may remain and the need for collaborative supply relationships will persist. Some levels of buyer-supplier integration may complement modularization ex post allowing problem solving for unforeseen design and supply chain management issues.

Furthermore, while today EVs' constitute a niche market, we do not know how OEMs strategies will evolve.

If EVs will be considered key in the competitive scenario, car-makers may be wiling to increase their control over these architectures, their sub-systems and components thus maintaining a high level of vertical integration no matter the level of EVs' modularity. In this case, OEMs would not narrow the scope of their knowledge because relying on the component specific knowledge owned by suppliers may be too risky. OEMs' knowledge necessarily have to span components boundaries (Brusoni et al. 2001; Cabigiosu, Camuffo 2012).

On the contrary, if EVs will be perceived as a marginal market, OEMs may not highly invest in components specific knowledge and be more willing to rely on the higher level of modularity that EVs may enable and to match it with loosely coupled and less-intensive supply relationships. In such cases OEMs may rely on available industry standards and external suppliers competences to develop EVs (MacDuffie 2012). For the sake of completeness, this scenario is likely to exist only if electrification *per se* will increase car's modularity level. Otherwise, specific OEMs effort and investments in components specific knowledge will be required to increase EVs modularity, thus increasing OEMs' level of vertical integration (Cabigiosu et al. 2012).

All in all, we expect that modular EVs will be coupled with modular supply chains, characterized by a high level of outsourcing and loosely coupled supply relationships, only if a) EVs technical characteristics *per se* increase the level of car's modularity; b) architecture stabilizes and presents minor modular/incremental innovations and b) OEMs do not perceive components specific knowledge and EVs as a source of competitive advantage.

Even in this scenario, modularity may complement and not fully substitute high-powered integration tools (Cabigiosu, Camuffo 2012).

6 Conclusions

Part of the modularity literature argues that modular products are produced by modular supply chains (Sturgeon 2002). This study, reviewing the existent literature, shows that EVs architecture is likely to become more modular than IC architecture and that EVs embody new technologies. Also, while EVs developed so far are mainly built on IC platforms, the next EVs models may be more performing and innovative if developed from dedicated platforms.

With high uncertainty about changes in technology and markets, stabilization of a modular product architecture is a two-edged sword. Some standardization may be necessary to allow first tier suppliers to focus on the complex subsystems in which they have distinctive capabilities. But too much standardization can become a barrier to systematic innovation and lock car-makers into a potentially obsolete product architecture.

This explains why firms, such as car-makers, are reluctant to commit to single product architecture and to a closed set of standard interfaces, hence constraining the development of product and organizational modularity. In these contexts, new hybrid forms of industrial organization that mix and match elements of modularity and integration are likely to emerge. These hybrid organizational responses reflect the fact that firms need to cope with highly complex technical and competitive challenges for which no ready-made organizational solutions exist.

Only at the point in which EVs will become overall mature products, characterized by a stable product architecture and a low level of technological change, OEMs will not perceive as key to maintain the control over externally supplied EVs' subsystems and modularity may play a role in fostering disintegration processes of EVs' supply chains. In this scenario, co-development practices might be less relevant and the advantages of relational and geographical quasi-rents negligible. Suppliers and buyers identity may become less important thus increasing the competition within the industry. Besides, even this may be a temporarily equilibrium that will resist till new technologies that foster the re-integration of the product architecture will be introduced (Fixson, Parker 2008).

Today, OEMs' strategic control over car's subsystems, such as the powertrain, and the EVs' technological evolution are likely to limit modularity in supply chains. The need to maintain a high level of control over the powertrain technology and its performance foster the integration and knowledge sharing with suppliers of complementary components and OEMs' reliance on collaborative supply relationships. The intensity of these relationships is also increased by the fluidity of the technology embodied into EVs' components.

Future studies should focus on the potential of EVs' market. If EVs will remain a niche market it is less likely that OEMs' strategies will focus on them, that dedicated platforms will be developed and that OEMs will heavily invest in innovative technologies. Also, scholars may analyze if suppliers with proprietary technologies will play a dominant role thus favoring the development of open standards, as happened in the PC industry with the Wintel platform.

References

Baldwin C.Y., Clark K.B., 2000, *Design Rules*, 1, *The Power of Modularity*, Cambridge (MA), MIT Press.

Batchelor J., 2006, «Modularisation and the Changing Nature of Automotive Design Capabilities», *International Journal of Automotive Technology and Management*, 6, 3, pp. 276-297.

Brown S., Pyke D., Steenhof P., 2010, «Electric Vehicles: The Role and Importance of Standards in an Emerging Market», *Energy Policy*, 38, pp. 3797-3803.

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

Campagnolo D., Camuffo A., 2010, «The concept of modularity in management studies: a literature review», *International Journal of Management Reviews*, 12, 3, pp. 259-283.

Cabigiosu A., Camuffo A., 2012, «Beyond the mirroring hypothesis: product modularity and supply-relations in the air-conditioning industry», *Organization Science*, 23, 3, pp. 686-703.

Cabigiosu A., Zirpoli F., Camuffo A., 2012, «Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry», *Research Policy*, forthcoming.

Christensen T.B., 2011, «Modularised eco-innovation in the auto industry», *Journal of Cleaner Production*, 19, pp. 212-220.

Clark C.B., Fujimoto T., 1990, «The Power of Product Integrity», *Harvard Business Review*, November 1990.

Colfer L., Baldwin C.Y., 2010, «The Mirroring Hypothesis: Theory, Evidence and Exceptions», Harvard Business School working paper 10-058, `http://www.hbs.edu/faculty/Publication%20Files/10-058.pdf`.

Cowan R., Hultèn S., 1996, «Escaping Lock-In: The Case of the Electric Vehicle», *Technological Forecasting and Social Change*, 53, pp. 61-79.

Cuenca R.M., Gaines L.L., Vyas A.D., 1999, «Evaluation of Electric Vehicle Production and Operating Costs», report sponsored by the United States Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies.

Dijk M., Yarime M., 2010, «The emergence of hybrid-electric cars: Innovation path creation through co- evolution of supply and demand», *Technological Forecasting & Social Change*, 77, pp. 1371–1390.

Doran D., Hill A., Hwang K.S., Jacob G., 2007, «Supply chain modularisation: Cases from the French automobile industry», *International Journal of Production Economics*, 106, 1, pp. 2-11.

Fine C., Golany B., Naseraldin H., 2005, «Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach», *Journal of Operations Management*, 23, 3, pp. 389-403.

Fine C.H., 1998, *Clock Speed – Winning industry control in the age of temporary advantage*, Cambridge (MA), Perseus Book.

Fixson S.K., Ro Y., Liker J.K., 2005, «Modularity and outsourcing: A study of generational sequences in the U.S. automotive cockpit industry», *International Journal of Automotive Technology and Management*, 5, 2, pp. 166-183.

Fixson S. 2003, «The Multiple Faces of Modularity – A Literature Analysis of a Product Concept for Assembled Hardware Products», Technical Report 03-05 of the University of Michigan, Industrial and Operations Engineering Department.

Fixson S.K., Park J.K., 2008, «The power of integrality: Linkages between product architecture, innovation, and industry structure», *Research Policy*, 37, pp. 1296-1316.

Furlan A., Cabigiosu A., Camuffo A., 2010, «Does modularity affect supplier integration? The role of component technological change», Best Paper Proceedings of the 2010 Academy of Management Meeting Montréal, Canada, 6-10 August 2010.

Galvin P., Morkel A., 2001, «The effect of product modularity on industry structure: the case of the world bicycle industry», *Industry and Innovation*, 8, 1, pp. 31-47.

Jacobs M., Vivkery K., Droge C., 2007, «The effects of product modularity on competitive performance», *International Journal of Operations & Production Management*, 27, 10, pp. 1046-1068.

Kulkarni A., Kapoor, A., Ektesabi M., Lovatt H., 2011, «Architectural proposals for electric vehicle design», Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition, November 11-17, Denver, Colorado, USA.

Langlois R.N., 2003, «The vanishing hand: The changing dynamics of industrial capitalism», *Industrial and Corporate Change*, 12, 2, pp. 351-385.

Larminie J., Lowry J. 2003, *Electric Vehicle Technology Explained*, John Wiley & Sons.

Lau A.K.W., Yam R.C.M., Tang E.P.Y., 2007, «The impacts of product modularity on competitive capabilities and performance: An empirical study», *International Journal of Production Economics*, 105, pp. 1-20.

MacCormack A., Baldwin C.Y., Rusnak J., 2010, «The architecture of complex systems: do core-periphery structures dominate?», Harvard Business School Working Paper 10-059.

MacDuffie J.P., 2012, «Modularity-as-Property, Modularization-as-Process, and 'Modularity'-as-Frame: Lessons from Product Architecture Initiatives in the Global Automotive Industry», Working paper, Wharton School, University of Pennsylvania, Philadelphia; and International Motor Vehicle Program, Massachusetts Institute of Technology.

Marletto G., 2011, «Structure, agency and change in the car regime. A review of the literature», *European Transport / Trasporti Europei*, 47, pp. 71-88.

Midler C., Beaume R., 2010, «Project-based learning patterns for dominant design renewal: The case of Electric Vehicle», *International Journal of Project Management*, 28, pp. 142-150.

Mikkola J.H., 2003, «Modularity, component outsourcing, and inter-firm learning», *R&D Management*, 33, 4, pp. 439-454.

Muffatto M., 1999, «Introducing a platform strategy in product development», *International Journal of Production Economics*, 60-61, pp. 145-153.

Ro Y., Liker J.K., Fixson S.K., 2007, «Modularity as a Strategy for Supply Chain Coordination: The Case of U.S. Auto», IEEE *Transactions on Engineering Management*, 54, 1, pp. 172-189.

Robertson D., Ulrich K., 1998, «Planning for Product Platforms», *MIT Sloan Management Review*, July 15.

Sako M., 2003, «Modularity and outsourcing: the nature of co-evolution of product architecture and organizational architecture in the global automotive industry», in Prencipe A., Davies A., Hobday M. (eds.), *The Business of Systems Integration*, Oxford, Oxford University Press, pp. 229-253.

Sanchez R., Mahoney J., 1996, «Modularity, flexibility, and knowledge management in product and organization design», *Strategic Management Journal*, 17, pp. 63-76.

Sierzchulaa W., Bakkerb S., Maatb K., van Weea B., 2012, «The competitive environment of electric vehicles: An analysis of prototype and production models», *Environmental Innovation and Societal Transitions*, 2, pp. 49-65

Sturgeon L., 2003, in: Yusuf, Shahid, Altaf, Anjum, Nabeshima, Kaoru (eds.), *The New Global Supply-base: New Challenges for Local Suppliers in East Asia, Forthcoming as Chapter Two in Global Production Networking and Technological Change in East Asia*, Oxford, Oxford University Press.

Sturgeon T., 2002, «Modular production networks: a new American model of industrial organization», *Industrial and Corporate Change*, 11, 3, pp. 451-496.

Ulrich K., 1995, «The role of product architecture in the manufacturing firm», *Research Policy*, 24, pp. 419-440.

Takeishi A., 2001, «Knowledge partitioning in the interfirm division of labor: the case of automotive product development», *Organization Science*, 13, 3, pp. 321-338.

Van Bree B., Verbong G.P.J., Kramer G.J., 2010, «A multi-level perspective on the introduction of hydrogen and battery-electric vehicles», *Technological Forecasting and Social Change*, 77, 4, pp. 529-640.

Van den Hoed R., 2007, «Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry», *Journal of Cleaner Production*, 15, pp. 1014-1021.

Wolter C., Veloso F.M., 2008, «The Effects Of Innovation On Vertical Structure: Perspectives On Transaction Costs And Competences», *Academy Of Management Review*, 33, 3, pp. 586-605.

Zirpoli F., Becker M., 2011, «The limits of design and engineering outsourcing: performance integration and the unfulfilled promises of modularity», *R&D Management*, 41, 1, pp. 21-43.