MANAGING COMPLEX, MODULAR PRODUCTS: HOW TECHNOLOGICAL UNCERTAINTY AFFECTS THE ROLE OF SYSTEMS INTEGRATORS IN THE AUTOMOTIVE SUPPLY CHAIN

Adrian E Coronado Mondragon*
Royal Holloway University of London, School of Management
Egham Hill, Egham, UK, TW20 0EX
TEL: +44 1784 414348
adrian.coronado@rhul.ac.uk

Christian E Coronado
School of Ocean Technology
Fisheries and Marine Institute of Memorial University of Newfoundland and Labrador
P.O. BOX 4920, St, John's, NLL, Canada
TEL: +1 (709) 778-0790
christian.coronado@mi.mun.ca

*** Corresponding author**

Abstract

Systems integrators can play a conspicuous role in automotive supply chains. A systems integrator is an organization with the capabilities to incorporate modular systems based on new technologies generated by its suppliers without its direct involvement. This work investigates the role of systems integrators at managing complex products with modular architectures under technological uncertainty in the automotive supply chain. For this research it was decided to rely on existing architecture typology that included high-to-low technological uncertainty in complex, modular products. The research methodology included case studies comprising two segments in the automotive industry. The results of the study show systems integrators in low technological uncertainty, such as coach and bus manufacturing, have to be able to redesign those architectures due to the implementation of unknown technologies in key individual components (i.e. transmission and engine technology). For complex product architectures under high technological uncertainty, the most important source of innovation still lies in the specialization of individual activities. The role of the system integrator in the automotive supply chain is reduced to create basic interfaces for the adaptation and incorporation of untested and uncertain technologies in the overall architecture. OEMs performed the role of systems integrators in this study.

Keywords: systems integrators; modularity; technology management; product architectures; supply chains

1. Introduction

Today many industries are facing an increase in competition that includes: shorter product life cycles, changes in demand behaviour, higher levels of product variety demanded by customers and fragmentation of traditional markets. As a result of this situation, companies in various sectors have shown growing interest in the study of modular product architectures that may benefit their businesses. The product architecture encompasses the information on how many components work together, how they are built and assembled, how they are used, and how they are disassembled (Fixson, 2005). Ulrich (1995, p. 419) stated that product architecture *"is the scheme by which the function of a product is allocated to physical components*" and it has a key role to play in the research and development (R&D) function of a company as decisions related to product architecture take place during the early phases of the innovation process.

Interchangeability and upgradeability associated to modularity are characteristics that have contributed to make modular product architectures popular among various industries. In its basic interpretation modularity has been acknowledged as a systemic innovation (Nystrom, 1990; Birchwall and Green, 2006; Campagnolo and Camuffo, 2010; Cabigiosu et al., 2013) and consequently autonomous innovations are held at sub-system level components, which through the effective implementation of interfaces are interchangeable and upgradeable. Recent efforts on the study of modularity have addressed the development of models that can help firms determine optimal modular production strategies under market uncertainty (Xiu et al., 2012; Pandremenos et al., 2009), ~~and~~ the effect of modularity on launch speed (Vickery et al., 2015) and the development of integrative frameworks devised for modular products that incorporate aspects related to product functionality and competitive market segments (Goswami, 2017).

The adoption of the modular architecture approach has enabled many industries to develop their architectures to levels of complexity that were unthinkable a few decades ago. Baldwin and Clark (as published in Garud et al., 2003, p. 162) indicated that modular architectures offer significant benefits that include: making complexity manageable, making parallel work possible and being tolerant of uncertainty. Classical examples of industries that have addressed the use of modular architectures can be found in the computer and work station industry (Iansiti, 1998) and the hi-fi audio industry (Langlois and Robertson, 1992). Specifically in the context of Complex Product Systems (CoPS), Miller et al. (1995) described the dynamics of modularization in the aircraft simulator industry. Another important contribution which describes the compatibility of modular systems in the context of CoPS was described by Brusoni and Prencipe (2001) in a study about the development of aircraft engines.

The previous paragraph provided some industry-based examples of modular architectures. These days the automotive industry represents a prime example of a sector where handling complex modular architectures has become an integral part of the business. In the case of the automotive industry, Fixson (2005) pointed out that the automobile market shows increasing numbers of niches, as well as increasing numbers of models in these niches (e.g., sports cars). Helper et al. (1999) and Sako (2003) foresaw, for automotive product architectures, the adoption of heavily modularized vehicles linked together by the effectiveness of the architectural interfaces. Specifically Helper et al. (1999) proposed that critical modular vehicle sub-systems are produced by the OEMs by outsourcing non-modular components.

The management of modular product architectures represents important challenges. One of the challenges relates to systems integration with implications to the supply chain. Increasing component modularity facilitates supply chain flexibility by reducing the need for specialized interfaces between an end-good producer and component suppliers (Sanchez and Mahoney, 1996). Therefore, it is expected that suppliers will continue to play a growing role in the management of product complexity through the extensive use of modular product architectures. In this scenario, the intervention of a systems integrator will be needed to ensure that a modular product architecture will meet the requirements of a specific final working product. Hobday et al. (2005) indicated that the main task of system integrators is to integrate multiple types of technology, knowledge and hardware equipment into a final working product or system. The impact of the tasks of the systems integrator will affect the supply chain of a modular product architecture.

This work examines the role of systems integrators involving technological uncertainty (low technology vs. high technology) in an environment characterized by highly-complex and highly-modular products in automotive supply chains. The OECD (2005) defined the automotive industry as a highly-developed industry, with very particular dynamics which in our opinion are worth exploring. In the automotive industry, technology actually drives changes in the relationships that govern the development and manufacturing of motor vehicles. In this research, we use case studies involving two major automotive sectors comprising bus and coach manufacturing and the development of by-wire systems (BWS). The results of the case studies are used to discuss the role of systems integrators and the particularities of managing complex product architectures in the automotive supply chain.

2. Modularity, CoPS, technological uncertainty and the role of system integrators in automotive supply chains

Modularity and Complex Product Systems (CoPS) are concepts closely related to each other. Modularity facilitates the creation of complex product architectures by developing sub-systems that can be designed independently and still work as a whole (Baldwin and Clark, 1997, 2003). Several authors have recognized the management of product complexity through the extensive use of modular product architectures (Camuffo, 2000; Garud et al., 2003; Fixson and Veloso, 2001; Daniilidis et al., 2012).

Modularity and complex product architectures are widespread in the automotive industry. In designing product architectures, which are capital intensive, automotive organizations have deliberately pursued modularity as a way to mitigate the trade-off between product variety and operational performance (Salvador et al., 2002; Ethiraj and Posen, 2013) and to tackle increased complexity (Brusoni and Prencipe, 2001). Under modular product architectures, platform products normally have a fixed number of modules with customization being achieved through variant modules to choose among a set of given options (Huang et al., 2007). According to Aydin and Ulutas (2016) platforms -in the most general sense- are intellectual and material assets shared across a family of products, and their use helps minimizing manufacturing complexity without compromising the ability to satisfy a variety of customer requirements. General wisdom in product platform design problems is that by considering commonality across different product profiles, manufacturing costs and product development time can be brought down (Goswami et al., 2017). Product architecture designs determine configurations and related variations, whereas the recombination and disaggregation of components into new configurations without losing functionality and performance are based on the level of modularization embedded in the product architectures (Mikkola, 2006). In the view of Fixson and Park (2008) it is well recognized that a majority of automotive products are becoming more modular over time and commonly associated with an industry structure changing towards higher levels of specialization.

Complex product architectures found in the automotive industry also represent a number of challenges. In fact, it is the authors' contention that in a stage characterized by further product modularization and firm specialization, it becomes very difficult for individual firms to break out of the established industry architecture via changes in the overall product architecture. On Complex Product Systems (CoPS), Li et al. (2014) suggested that because of the high technical content and multi-dimensional complexity of CoPS, the existing module partition approach cannot identify the module of CoPS effectively and efficiently. Dedehayir et al. (2014) argued that the nature of CoPS industries tends to be characterized by multi-firm alliances that are formally established to enable innovation. Clark and Fujimoto (1991) indicated that product complexity can be affected by decisions about innovation and variety and the level of supplier involvement.

Modularity and complex product architectures most likely require firm collaboration in an environment characterized by different levels of technological uncertainty. Prencipe (2003) claimed that the level of collaboration between competing and complementing firms determines the turbulent nature of complex product architectures. Prencipe (2003) argued that "*Firms are not islands but are linked together in patterns of co-operation and affiliation. Planned co-ordination does not stop at the boundaries of the individual firm but can be affected through co-operation between firms.*" Prencipe and Tell (2001) and Dosi et al. (2003) argued that the participation of several firms through strategic alliances, most of them of a temporary nature, are required to successfully advance product architecture constructed on large technical and scientific domains.

Firm collaboration can be seen as a way to deal with technological uncertainty at a time when being able to react to uncertainties in technology and market streams has become the minimum survival skill in the increasingly chaotic world of the science-based enterprise. Along with technology novelty, technological uncertainty is a common source of uncertainty in product innovation (Chen et al., 2005). Firm collaboration is an element that can be related to managing complex modular architectures. In the motor vehicle industry, Coronado et al. (2009) investigated the way automotive OEMs and suppliers relate to each other when technological specialization produces complex electronic/electric vehicle architectures. The end result according to them is the creation of interdependency among all members of the automotive innovation network. This interdependency is strategic, and strategic relationships tend to foster collaboration between organizations and their suppliers.

On the evolution of firm collaboration the consortium has raised its profile in recent years as an alternative collaborative arrangement that can be used by organizations facing the difficulties of managing complex product architectures, especially when knowledge and understanding of control policies, architectural choices and effective extent of supplier-buyer collaboration are all critical for effectively managing product architecture. The typology of collaborative arrangement for complex industries defines consortia as joint-bidding arrangements made by several firms each adding value to the group (Kamel, 2006; Ili et al., 2013). Collaboration cannot ignore the involvement of systems integrators.

System integrators represent an inherent element in the development and adoption of new automotive technologies which show the development behavior of complex products and systems. Takeishi and Fujimoto (2003) argued that modularization in the automotive industry occurs at different levels and it evolves through the dynamic interaction of systems integrators and suppliers. Iansiti (1998) stated that *"ultimately, the mastery of technology integration is critical because it creates the capability to manage technological change."* For an organization this means to be able to "*navigate between technological trajectories, fighting inertia and adapting to and influencing an uncertain market context."* Despite the fact that automobiles are mass-produced goods, the development and design of automotive architecture are CoPS in nature. This means that design of automotive architectures are capital goods, which are highly complex and of high value (Miller et al., 1995; Hobday, 1998). The automotive architecture has been an issue of conflict between scholars for many years as some authors contend that the automotive industry is integral in nature, thus making it difficult to further modularize systems (Fujimoto, 1999). However, published academic work claims that automotive architectures are developed in an open modular systemic architecture, rather than closed integral architecture (Helper et al. 1999; Doran et al. 2007). We subscribe to the latter perspective.

Given the purpose of this research work, the automotive supply chain is particularly attractive for the study of complex product architectures because of supplier involvement at various stages. One important characteristic in this industry is the high involvement of suppliers in value adding generation (Quesada, et al., 2006; Wagner et al., 2008; Lockström et al., 2010). Other ramifications clearly associated to supplier involvement include firm collaboration such as the level of cooperation found in a supply chain and the effectiveness of cooperative actions (Zhang et al., 2009). Additionally, we can find the capability to control the collaboration between the automotive OEM and its suppliers in order to enable the success of supplier integration (Tang and Qian, 2008) or guidelines to increase the effectiveness of R&D collaboration for complex new products in the automotive sector (Binder et al., 2007).

Based on the discussion of the literature comprising technological uncertainty, modularity, complex product architectures and systems integrators, the following research questions were formulated:

- *How the level of technological uncertainty affects the role of system integrators for complex products with modular architectures in automotive supply chains?*

- *How the level of technological uncertainty determines the involvement of technological consortia in systems integration for complex products with modular architectures in automotive supply chains?*

The scope of this research focuses on highly-complex and highly-modular product architectures. Hence, low and medium levels of architectural complexity and modularity are not part of the variables considered for this research.

3. Research methodology: case methodology in automotive supply chains

As previously stated the purpose of this research work is to investigate the role of systems integrators at managing highly-complex and highly-modular product architectures with different levels of technical uncertainty in automotive supply chains. Specifically this research provides a robust empirical analysis, but most importantly it explores specific strategies that are used in the automotive industry and which are discussed in the case studies.

The research questions in this work were formulated to provide the direction of inquiry, and enable a connection between the research and its practical and theoretical contributions (Dubé and Paré, 2003). The research question agrees with Yin's (1994) guidelines that case study research should generally be used to answer *how* and *why* questions. A positivist case study deals with deductive theory testing and addressing, reliability and increasing levels of freedom. The qualitative case study is an empirical research that primarily uses contextually rich data from bounded real-world settings to investigate a focused phenomenon (Barrat et al., 2011). The cases selected focus on the *how* in the context of rich empirical evidence.

The use of industry cases is to address key points highlighted by Miles and Huberman (1994) including the possibility to understand processes and outcomes of cases and causality. An important element of the case study methodology is the unit of study which for this research consists of the identification of a large automotive technical system. Buganza et al. (2009) stated that the case study methodology approach allows a holistic and contextualized analysis and it is properly suited for the initial phases of the exploratory nature of research work. Our study is exploratory with a small sample, albeit representative of the entirety of the automotive industry. This fact seriously limits viability and reliability of quantitative methods and tools (i.e. surveys).

Specifically for this research, qualitative case studies accurately portray the technological diversity of the automotive industry. Furthermore, these cases were selected upon the recommendation of a panel of experts and scholars with backgrounds in innovation management, modularity, and project management in the automotive industry. These experts were part of a governing body of the former program "Managing of Innovation in the New Economy (MINE)" at the Ecole Polytechnique de Montréal. Furthermore, the architectures selected for the study were defined using an adapted version by the authors of this research of the complex technological systems typology developed by Hobday et al. (2005).

Figure 1 shows two major automotive segments investigated, bus and coach and automotive by-wire systems, which represent large technical systems with different levels of technological uncertainty. Both segments have particularities suitable for this research because some important characteristics. The bus and coach architecture has been typically considered high-complexity, low-technological uncertainty automotive application. The bus and coach architecture was selected to reveal the role of systems integrators and its relation with key modular systems developers which are part of the supply chain. The by-wire systems architecture was selected for representing high complexity and high-technological uncertainty applications. Automotive by-wire systems represented by brake-by-wire (BbW) and steer-by-wire (SbW), are systems with a great number of loose ends, making them very appealing from a research stand point since they can illustrate the mechanics of adoption of new technologies in modular systems which are integrated within a larger technological system.

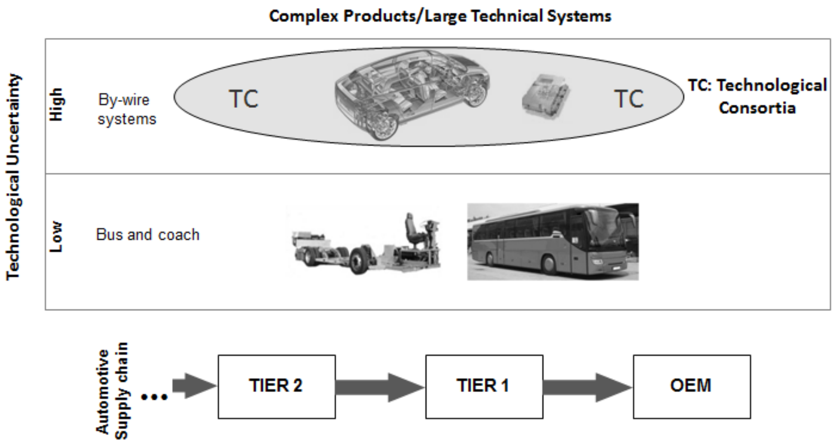

Figure 1. Representation of the multiple case study approach comprising large technical systems selected for this research

Based on the adapted technological typology of the case studies shown in figure 1, the case research methodology was applied to the participant organizations listed in table 1.

Case sector	Region of origin	Type of Company	Product	Sales Volume (Million of USD)	Source
Bus and Coach	Scandinavia	OEM	Buses	≥ 10,000	EM, EM
By-wire systems	Scandinavia/North America	Tier 1	Ball Bearings, Mechatronic equipment	≥ 5,000	ED
By-wire systems	Northern Europe	OEM	Whole cars	≥ 10,000	ED
Bus and Coach	Scandinavia and North America subsidiary	OEM	Buses	≥1,000	CEO, ED(S), VPS
By-wire systems	Northern Europe/East Asia	Tier 2	Automotive Semiconductors	≥ 5,000	ED, ED
By-wire systems	USA/Northern Europe	OEM	Whole Cars	≥10,000	GED, EED

Note:
CEO: CEO; CEO(S) CEO of Subsidiary; ED: Engineering Director; ED(S); Engineering Director Scandinavia; EM: Engineering Manager; GED: Global Engineering Director; VPS: Sales Vice-president

Table 1. Information about the participant companies in the study

Table 1 shows the information about the participants in this study grouped around the two automotive segments identified for this research. The use of two major automotive segments and various companies provides benefits such as increasing external validity (Yin, 1994; Lockström et al., 2010). As for complementary data to the interviews, much information about the participants' organizations was gathered in the form of documents such as firms presentations, financial statements, marketing brochures and promotional materials. Respondents to the case study included CEOs, engineering managers, engineering directors, a global sales vice-president and one global post sales service manager. Additionally the analysis of the case studies involved the participation of respondents from one North American automotive consultancy firm which included a research director and a senior research scientist. Also the senior vice-president of a North American Manufacturing Association participated in the study.

In both major automotive segments investigated in this research, the bus and coach architecture and the by-wire systems architecture, the role of systems integrators is performed by the OEMs. The analysis of the cases will allow us to investigate in detail the proposed research question on how the level of technological uncertainty affects their role as systems integrators involving complex products with modular architectures in automotive supply chains.

The scope of the implications of systems integrators is multi-tier, as it involves the participation of OEMs and suppliers in the automotive supply chain. Beyond focusing only on OEMs and suppliers, in this research the participation of an automotive consultancy firm and a manufacturing association is key to gain a clear and comprehensive understanding of how technological uncertainty affects the role of systems integrators when it comes to dealing with complex products with modular architectures.

The emphasis on collecting data through semi-structured interviews was to accomplish what has been referred to as comparability while ensuring an unobstructed flow of narrations (Bryman, 2004; Lockström et al., 2010). The research protocol included a questionnaire that was developed in conjunction with a panel of experts in the field of automotive technology. The appendix section shows some of the questions asked to the interviewees from the organizations that participated in this study. It is important to highlight that during the interviews respondents were free to steer and expand the answers to some questions based on the aspects they wanted to emphasize based on their own experience, technological uncertainty and conditions facing their automotive segment. As part of the research protocol, face-to-face interviews were conducted (most of them) as well as telephone conference calls. Interviews were recorded (unless disallowed by the informant), transcribed and coded in order to allow for reliability and traceability as indicated in the guidelines provided by McCutcheon and Meredith (1993).

4. Case studies presentations

This section comprises the description of the industry cases associated to two major segments in the automotive industry which are used to analyze the role of systems integrators in complex product architectures in automotive supply chains and showing different levels of technology uncertainty.

4.1 Case A. Long Distance Coaches and Transit Buses

The bus segment has mastered modular architectures and interfaces in a better way than OEMs of passenger cars. Still, this goes beyond the mere implementation and management of modular architectures. Body builders (BB for coaches and small vehicle integrators (SVI)) -such as North American dedicated Transit Bus Manufacturers- represent the closest industrial practice to the so called "*mass customization*" through the effective management of modular architectures. This takes place as flexible interfaces between the loop comprising sales-purchasing-engineering/validation-manufacturing and the correct management of non-dedicated equipment. BBs that put these elements in practice can ensure customer satisfaction by allowing architectural product modifications which for OEMs of passenger cars would be impossible to achieve (Holweg and Pil, 2004). This phenomenon is explained by the mechanics of the transit bus/coach segment for which the vast majority of business transactions happen on business-to-business (B2B) basis. Therefore the end customer (mostly bus operators) can actually steer the vehicle configuration according to its desired specification.

Figure 2 depicts the mass customization nature of the segment and also shows the disintegration process from complex product systems integrators. Figure 2 shows how modular architectures for long distance coaches are integrated.

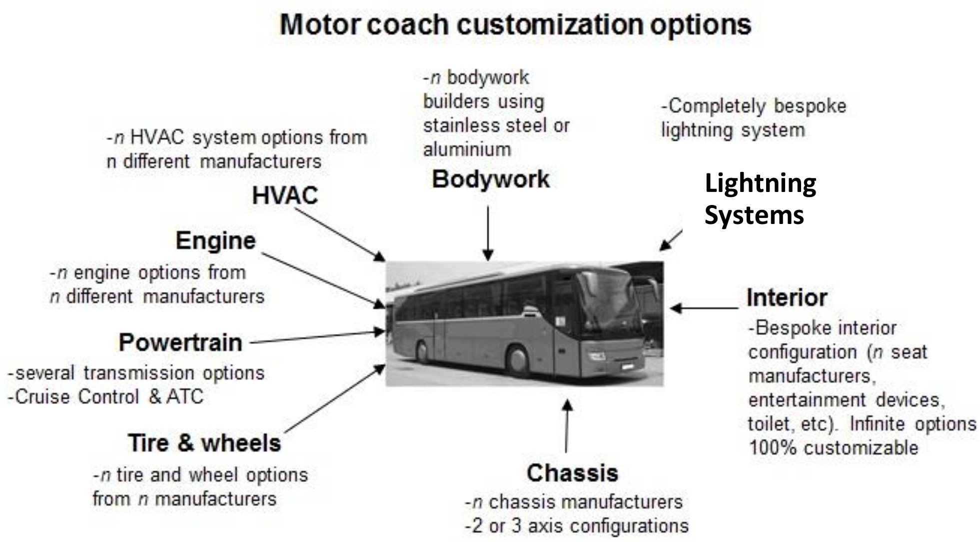

Figure 2. Mass customization nature found in the Transit Bus and Long Distance Coach Segment

Thus in the transit bus and long distance coach segment, commonly labelled as Class 8 heavy duty vehicles, the ultimate benefit of modularity, economies of substitution, upgradeability and inter-changeability (Garud et al., 2003) are achieved, not by the architecture designer (such as the OEM or Body Builders) but by the customers, which are usually large fleet operators with sufficient leverage power to modify vehicle configurations and interchange body modules with chassis modules at their will. This adds to the fact that major automotive suppliers for Class 8 vehicles (companies like Voith, Allison, ZF, Hella, Arvin-Meritor, TRW, etc.) are technological innovators with proprietary applications, which are included as sub-system components in several automotive modular architectures. Typical subsystem components include automatic transmissions, lighting systems, braking and exhaust systems among others.

4.2 Case B. Automotive By-Wire Systems

Typically, by-wire systems comprise those systems that have substituted mechanical and hydraulic components by the use of mechatronic actuators and on-board electronic control units (ECU) or dedicated computers for aeronautic or automotive purposes. Nowadays, by-wire systems are in full utilization in the aeronautical industry where modern aircrafts have replaced mechanic or hydraulic flight control systems by full by-wire applications. The first full by-wire aircraft was the NASA F-8C Crusader, in 1972 (www.nasa.gov). The automotive electronic architecture has been in constant evolution; current automotive architectures have more than 80 ECUs which need to communicate between them. Among the most important efforts of automotive OEMs and suppliers to enhance communication effectiveness within vehicle components was the development of a serial communication protocol called controller area network (CAN).

Another automotive complementary *bus*[1] protocol (electronic architecture), which is frequently used for automotive purposes, is the local interconnect network (LIN) *bus*. The specification of this protocol allows the communication of sensors and actuators operating at 12V. Mainly this *bus* is used for vehicle body applications such as sunroof actuators, intelligent wipers, HVAC and other body electronics applications. The LIN *bus* has a maximum speed of 1.92 Kbps over a maximum cable length of 40 metres (www.interfacebus.com). Most of the times the LIN *bus* is used as a sub-system within a CAN vehicle architecture (www.ni.com; www.interfacebus.com).

The FlexRay protocol is a communication network which is a fault-tolerant, high-speed *bus* system (www.freescale.com/webapp/sps/site/overview.jsp?code=FLEXRAY; www.ni.com). FlexRay provides error containment and delivers time determinism performance needed for by-wire critical applications (http://www.ni.com/white-paper/3352/en). Fault tolerance is achieved by allowing single or dual-channel redundancy communication; hence, critical safety applications have the required critical redundancy since data is transmitted using two channels. Typically FlexRay's data transfer rate is 10 MBit/sec on two channels or a gross

[1] Unless otherwise stated, *bus* refers to a subsystem that transfers data between computer components inside a computer or between computers.

data rate up to 20 Mbit/sec. Figure 3 depicts the use of FlexRay as an architecture supporting various by-wire applications developed by different suppliers and used in a finished product, in this case a motor vehicle. For example figure 3 shows steering-by-wire, brake-by-wire, gas-by-wire (throttle) and there can be many more.

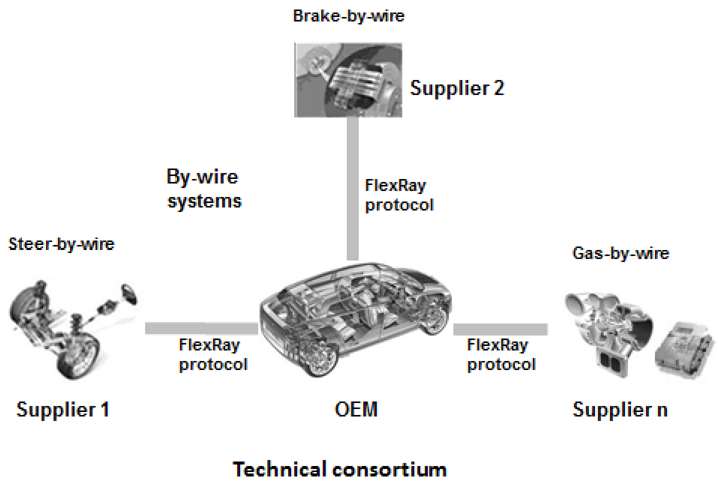

Figure 3. Illustration of the use of FlexRay to support different by-wire automotive applications

The functionality of by-wire systems is based on the communications and interaction between several ECUs and other electro-mechanical actuators and the feedback that the system delivers to the vehicle operator. Hence, among the most important issues for successfully implementing applications is the development of reliable, accurate, self-redundant, fault-tolerant and dependable communication software protocols and the related equipment needed to maintain effective communications (e.g. sensors, power supply, microprocessors, etc.) This guideline is based in accordance to IEC61508 and ISO26262 standards for programmable electronic safety related systems (Erkkinen and Conrad, 2007).

5. Analysis of the role of systems integrators under complex modular architectures and different levels of technology uncertainty

5.1 Discussion on Transit Buses and Long Distance Coaches

The economics of heavy duty passenger vehicles are very different from passenger cars. Transit buses and coaches are manufactured by the thousands: meanwhile, passenger cars and heavy duty trucks are manufactured by the hundreds of thousands. As it was observed by the participants of this segment, this fact drastically reduces the economic incentive and resources to explore new technologies specifically for buses; hence, manufacturers, specifically full-vehicle manufacturers such as Volvo or Daimler-Benz, spin out their technologies developed for other segments (i.e. passenger cars and heavy duty trucks) and adapt them for use in their buses and coaches. Collaboration between OEMs in this segment is practically non-existent.

While conducting our research for this segment it was possible to appreciate that independent manufacturers such as those in North America (e.g. New Flyer, MCI and others) have to constantly enhance their vehicle integration capabilities (in technology integration and manufacturing efficiency) to maximize efficiencies. In this segment architectural control is exerted by suppliers and customers. As stated by the Sales VP of a global bus manufacturer (from Northern European origin) with operations in Latin America:

> *"Clients do exercise control over architectural decision not only by setting stringent performance goals on the vehicle, sometimes they very actively participate in architectural decision and styling clinics. Clients are very knowledgeable buyers, they are indeed able to modify the vehicle architecture and specs, if we do not yield to their suggestions they simply will find someone else that will..."*

The study revealed that independent vehicle integrators and bus divisions of OEMs (such as Volvo Bus Corporation or Daimler Commercial Vehicles/Setra) are relatively small in comparison with the size of other automotive organizations. Hence, independent vehicle integrators depend technologically on their system providers and system providers are not likely to take over integration tasks due to the huge liabilities involved in the tasks of integration (even for small vehicle manufacturers). The study of this segment revealed that it is important to understand that the role of systems integrators in the heavy duty vehicle sector is bound not only to technological developments but most importantly constrained by political and legal considerations, which may hinder the implementation of developments and new technologies.

5.2 Discussion on by-wire Automotive Applications.

By-wire automotive applications show a very particular level of participation and cooperation; therefore, the characteristics observed in by-wire automotive applications regarding the role of systems integrators and management of complex product architectures motivated the following discussions using direct quotes from the individuals who participated in the interviews.

Multi-firm technological developments; the FlexRay standard

The FlexRay protocol standard was developed originally by the BMW group as a ByteFlight passive protocol for airbag release and other short-time release applications. Former Daimler-Chrysler joined BMW to improve and further develop the ByteFlight for by-wire applications to ultimately become the FlexRay protocol. The FlexRay consortium is integrated by several OEMs, Tier 1 suppliers and several silicon vendors (automotive electronic circuitry manufacturers). The main objective of the FlexRay Consortium is to develop (with the collaboration of all its members) the specifications of the FlexRay protocol as a communication standard for on-board vehicle communication. The study of the FlexRay standard shows that in order to achieve this intensive collaboration among the parties involved, a common goal is required. All parties involved agreed that the common goal would be to extend the technological and financial resources of the FlexRay Consortium. In this regard, the two Engineering Directors (ED) of automotive applications from a major silicon vendor and the Research Director (RD) of an automotive consultant participating in the case study agreed on the importance of strong cooperation among parties. The ED of a silicon vendor located in Northern Europe claimed that for automotive electronic purposes:

> *"Automotive innovation is only attainable by the strong cooperation of OEMs, Tier 1 and other suppliers..."*

In the light of technological uncertainty investigated in this research, specialization of each individual activity performed by members of a given innovative network emerged as an important factor. During this research the same executive indicated that specialization is the most important asset that a firm such as Tier 1 or silicon vendor can have since the criticality of the automotive electronic architecture may restrain architects to change to other suppliers since these products are unlikely to become commodities.

When investigating suppliers in electronic products architectures taking a more proactive role and more responsibilities for integrating sub-systems by Tier 1 and other suppliers (with the potential to take on the role of systems integrators) the ED at a key Tier 1 supplier of by-wire applications (ball bearings and mechatronic equipment) participating in the study expressed the following:

> *"...We all have very clear and defined functions; so it is very unlikely that Tier 1s and other suppliers are trying to encourage changes in their roles; especially if these do not concern them…"*

An ED of a silicon vendor located in Northern Europe expressed the following:

> *"If OEMs seem not to understand the electronic architecture and are losing control of it; we will partner with Tier 1 and silicon vendors to enable the OEMs to recover from this. It is actually bad for Tier 1 or silicon suppliers if OEMs ever lose control of the architecture; that means that they (Tier 1 and silicon vendors) will have to take over the task of integration; and they -Tier 1 and silicon suppliers- don't have an interest in doing that...."*

The risk of litigation on product faultiness and other legal considerations plays a key role in stopping the migration of Tier 1 and other automotive suppliers to higher roles, especially to systems integration. In reference to this point, the unwillingness to move toward systems integrators, the RD from an automotive consulting and research centre in North America agreed that potential litigations have stopped suppliers from becoming systems integrators. Actually, a Senior Research Scientist (SRS) from the same research centre expressed the following:

> *"...Liabilities and potential litigations risks are the main deterrents for Automotive Suppliers not to become OEMs (or system integrators)."*

5.3 Highlights of the case studies

In this research two segments of the automotive industry representing different levels of technological uncertainty were analyzed and portrayed by: a) low-technological uncertainty and high complexity (transit bus and long distance coach body building and vehicle integration) and b) high-technological uncertainty and high complexity (by-wire systems). Figure 4 depicts the location of the automotive segments investigated in the multiple cases based on technological uncertainty, the level of participation and cooperation in technological developments and the possibility of suppliers taking over the role of systems integrators.

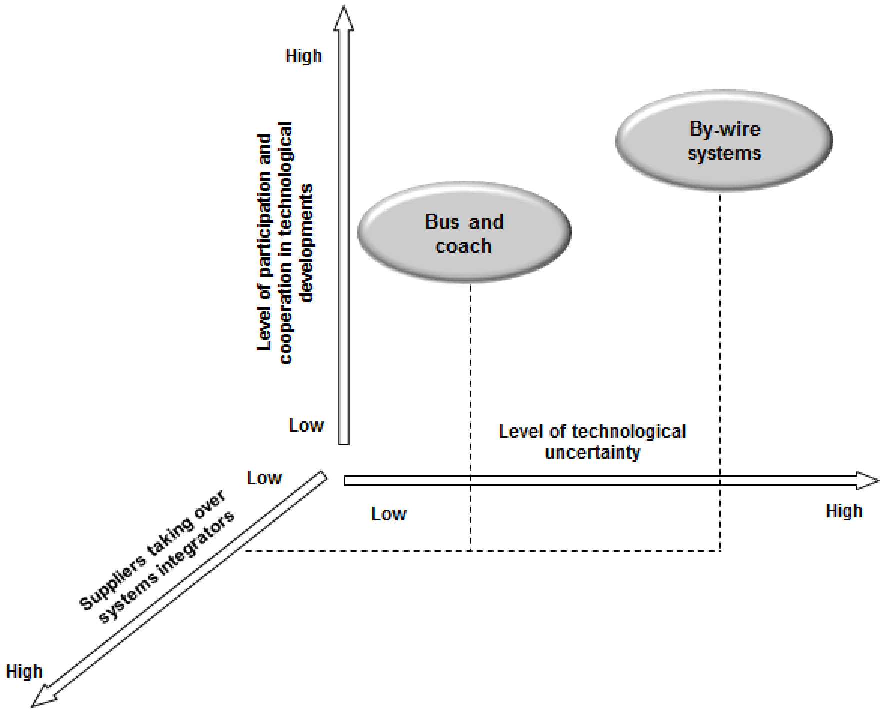

Figure 4. Location of automotive segments based on technical uncertainty, level of participation and cooperation and chances of suppliers taking over systems integrators

Based on the observations of the case studies, figure 4 shows by-wire developments represent a high level of participation and cooperation in technological developments among all parties involved in high technological uncertainty. As previously mentioned, the risk of litigation on product faultiness and other legal considerations play a key role in stopping the migration of Tier 1 and other automotive suppliers to systems integration. In contrast, bus and coach manufacturing represents a low level of participation and cooperation in technological developments, in an environment of low-technological uncertainty. In the latter case of bus and coach segment, suppliers (independent vehicle integrators) depend technologically on their system providers and system providers are not likely to take over integration tasks.

Although in the bus and coach segment independent manufacturers have to constantly enhance their vehicle integration capabilities to maximize efficiencies, the control of the architecture is exerted by suppliers and customers. For by-wire systems/electronic product architectures – FlexRay, Tier 1 and silicon suppliers do not want OEMs to ever lose control of the architecture. Table 2 summarizes the findings from the bus and coach manufacturing and by-wire/electronic product architecture – FlexRay automotive segments investigated in this research.

Automotive Architecture	Architecture Complexity/Level of Technological Uncertainty	Architecture characteristics	Characteristics of architectural control	Level of Participation and Cooperation
Long Distance Coach and Buses (Class 8 Vehicles)	High/Low	Technology integration and mass customization of vehicles	Leadership exercised by suppliers and customers	Limited to medium collaboration. Technical stability of the architecture does not foster much collaboration between OEM – Automotive Suppliers and almost inexistent between OEMs
By-Wire Systems Electronic product architectures – FlexRay	High/High	Knowledge share and stability of the product platform	Technological leadership is exercised by all members of product architecture. Not clearly defined line of who's controlling the architecture.	Very high. Technological uncertainty forces collaboration as a form to share resources, risks and liabilities. Stability of the architecture is beneficial for all the members of the architecture. Technical uncertainty is driver of architectural openness

Table 2. Findings from the two automotive segments investigated

Regarding the answer to the research question on how the level of technological uncertainty affects the role of system integrators for complex products with modular architectures in automotive supply chains, the findings from the study suggest that in complex and low-technological uncertainty architectures dependence lies on technology integration and mass customization of vehicles, characteristics of architectural control is dependent on leadership exerted by key suppliers and customers, similar to Gawer and Cusumano (2002) theory of platform leadership. In terms of level of participation and cooperation among participants, it is characterized for limited to medium collaboration. Our findings reveal that technical stability in architectural platform at best fosters limited collaboration between OEM and automotive suppliers or at worst is inexistent. Apart from the long distance coach and bus manufacturing investigated here we believe that the same principles may apply to the manufacturers of special purpose vehicle such as fire engines, highly customized luxury yachts manufacturers, and luxury motorhomes manufacturers.

In architectures where high-technological uncertainty is present, table 2 shows that in terms of architectural control and technological leadership, these are exerted by all members of the product architecture. In terms of level of participation and cooperation, a complex architecture with a high technological level of uncertainty is characterized for having very high levels of participation. Our findings show that technological uncertainty compels the parties to actively collaborate as a form to share resources, risks and liabilities. Moreover, architectural stability is beneficial for all the members of the architecture, since this brings a clear definition of roles and responsibilities for the system integrator and other participants in the architecture.

The arguments presented above answer the second question of this research on how the level of uncertainty determines the involvement of technological consortia in systems integration for complex products with modular architectures in automotive supply chains. For the case of OEM systems integrators, technological consortia appear to be the preferred alternative for a collaborative arrangement, given the difficulties of managing innovation for highly complex product architectures under high technological uncertainty. On the one hand it is highly unlikely an OEM will go alone when dealing with high complexity and high-technological uncertainty applications like by-wire systems architectures, simply because the risks associated with failure are too high. On the other hand, it is highly unlikely the use of technological consortia will be adopted in applications characterized for low levels of technological uncertainty like the bus and coach architecture.

6. Conclusions

This research has provided the opportunity to address some important elements on how the level of technological uncertainty affects the role of system integrators for complex products with modular architectures in automotive supply chains. The results of the empirical research confirmed that for the automotive industry with a complex product architecture the level of technical uncertainty influences the level of supplier participation and cooperation. Thus, complex, low-technological uncertainty architectures are likely to have suppliers leading component innovation but also steering the architectural developments with system integrators. In the same way for complex architectural products with a high level of technical uncertainty, suppliers may influence the product architecture at the component level.

This work makes a contribution to the body of knowledge by focusing on the use of modularity and the role of systems integrators to tackle the challenges associated with technological uncertainty in complex product architectures characterizing the automotive industry, which comprises a modular multi-tier supply chain. The analysis of the multiple cases showed an increasing participation of suppliers in the development of complex architectures with low-technological uncertainty, such as transit buses and long distance coach manufacturing. This study shows that it is possible to see OEMs (transit bus and long distance coach manufacturers) engaged in adapting practices associated with their organizational competencies to the new technologies developed by suppliers, which means being aligned to the technological leadership exerted by specialized suppliers. Henceforth, the main technological capability for an OEM is being able to adapt to new technologies in a flexible manner. It is important to mention that these kinds of automotive manufacturers manage complex product architectures through their flexible manufacturing capabilities by creating truly customized vehicles.

This study, however, did not show any evidence that OEMs or vehicle integrators are losing their technological capabilities or technological expertise in fields such as advanced electronics, data bus development and vehicle integration. These technological developments require specialized knowledge and competencies, which most of the time are outside the competence spectrum of OEMs. Nonetheless, technological consortia, such as FlexRay (originally established by OEMs), were created to bring together automotive suppliers and vendors who are specialists in their domain area. The unique aspect of these consortia is their internal mechanics for generating further technological advances. For technology practitioners and scholars the study of systems integrators represents several challenges, not only because of the characteristic dynamism of complex product architectures but due to the need to coordinate and commit actions of many architecture developing parties.

Future studies about the role of systems integrators for complex products with modular architectures under technological uncertainty offer significant opportunities. In particular, future research work will have to address the developments currently taking place involving the electrification of vehicles. Powertrain electrification is pushing automotive architectures towards full-blown modularized architectures. We foresee that these complex modular architectures will comprise the use of lightweight materials such as carbon fibre reinforced polymers (CFRP) in several modular components, by-wire systems, modular battery packs and the required cooling systems that can be integrated in one module and electric drive modules. A glimpse of the future of an electrified automotive architecture maybe similar to General Motors proposed "skateboard architecture", Mercedes-Benz's Concept EQ for powertrain, or the Nikola Motor Company architecture for electric heavy duty trucks. Technological developments in modular platforms may impact the costs of developing and producing electric vehicles. As a result the next generation of electric vehicles may become more competitive, affordable and with more body style options.

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