A Multi-dimensional decision framework for modular value transfer activity

Abstract

This paper explores the key dimensions and value-adding elements of a supply chain delivering cockpit modules to an automotive assembly operation in the United Kingdom. The findings demonstrate that supplying on a modular basis is influenced by the initial design decisions of the Original Equipment Manufacturer (OEM), the capabilities of the Module supplier and the ability to offer greater levels of customization in a high-volume environment. The research articulates the findings through the concept of the "Dimensions of Modularity" which seeks to demonstrate the key decision areas in a modular context and extend the concept of "Value Transfer Activity" within a modular context.

Our research provides insights into the specific dynamics of a module supply chain from OEM through to Modular supplier and a supplier of sub-modules. From this research, those involved in developing modular solutions can determine the multi-dimensional issues that need to be addressed to ensure that the supply chain is effectively connected and value transfer implications are accommodated and maximised. By adopting a single supply chain approach to exploring the impact of modular practices this paper provides valuable observations into an area of supply chain and operations management that is becoming increasingly relevant to both academic and practitioner communities.

Key words: Modularity, Supply chain management, Automotive

1. Introduction

In 1965 Martin Starr observed that modular product architectures allow firms to design a large variety of product variants by combining modules into a complete system where firms can fulfil mass customization without the need to perform unforeseen engineering, sourcing and manufacturing activity (Starr, 1965). Starr correctly observed that variety based solely on marketing effort is not sufficient in sophisticated markets and that variety needs production involvement. Drawing upon this theme, Salvador et al (2004:382) stated that modularity can enable the firm to 'reconfigure its supply, manufacturing and distribution networks (or supply chain) to meet the challenge of mass customization. In fact, product modularity eases the outsourcing of production activities to a firm's suppliers, so that internal manufacturing operations may be simplified.' In essence, modular production separates the production process into a primary transformation process of inputs and raw materials into generic modules and components, and, a secondary assembly process that combines generic parts in a maximum number of combinations into finished goods. Modularity has gained traction in many aspects of automotive production and is now regarded as a means to accommodating mass customization in a cost effective manner (Doran et al., 2007).

Understanding the impact of modularity on suppliers that add value within the supply chain is critical for our understanding of the dynamics associated with modular production. Indeed, Salvador et al. (2002) observed that there is very little research exploring the impact that the decision to adopt a modular design has upon the operations and supply chain management activities of actors involved in value creation activity. Furthermore, because postponement strategies involve product development and module suppliers in the value chain, collaboration and integration is both inevitable and necessary between multiple functions or organizations (Hsuan & Skjøtt-Larsen, (2007); Caniato & Größler (2015).

(often regarded as the Dashboard of the car) A cockpit module is extremely complex and normally consists of an array of complex electronics, navigation systems, airbags, heating and ventilation systems, structural shaping, digital displays and switching, and, in an increasing number of cases, the steering column (with its own array of functionality) and foot pedals (acceleration, clutch and brake). Furthermore, when a customer buys a car from a dealer they are then allowed to customize elements of the cockpit module to reflect their own personal preferences; in essence, this means that each cockpit module can only be fitted in one car. Developing and manufacturing modules, delivering them just in time and just in sequence is a significant challenge to all those parties involved in their provision and present an array of challenges. Specifically, the provision of modules requires a high level of supplier communication and integration in order to ensure that the potential benefits of modular provision can be secured.

Reflecting the cockpit details described above, the aim of this paper is to examine how the decision to adopt a modular approach influences the key stages of the modular supply chain and to highlight the issues faced by OEMs, Module Suppliers and Module Parts Suppliers. Specifically, this research investigates the ways that the decision to adopt a modular approach impacts the value-adding activities of suppliers in a modular supply chain. The paper contends that a modular approach should be considered in a more holistic manner by articulating the implications of the modular design decision and the subsequent impact that this has upon the accrual of modular benefits, the increasingly important role of the module supplier and the upstream implications associated with the provision of modules.

The paper is organised as follows: Section 2 explores the literature underpinning our research by examining the nature and scope of modularity and the supply chain dimensions associated with modular provision. Section 3 presents our methodological, whilst section 4 details key findings. Section 5 provides a discussion of the primary findings whilst section 6 details the managerial implications of our research.

2. Modularity perspectives at the firm and supply chain level

This review begins with an exploration of the features of modular design and is followed by an examination of how modular design influences the configuration and operations of the supply chain and logistics provision.

2.1 Design perspectives of modularity

Baldwin & Clark . (1997:84) described modularity as "building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole." In a similar vein, Macduffie, (2013: 8) observed that modularity "is a design property of the architecture of products, organizations and interfirm networks; modularization is a process that affects those designs while also shaping firm boundaries and industry landscapes; and modularity is a cognitive frame that guides categorization and interpretation of a wide array of economic phenomena." In essence, MacDuffie's observations encapsulate the complex nature and scope of what is often referred to as 'Modularity' and the observation that adopting a modular approach stems from the design and architectural decisions that are developed to accommodate modularity. Much of the literature makes reference to the conceptual work of Ulrich (1995: 419) who succinctly articulated the importance of "product architecture," which he described as "the scheme by which the function of a products is allocated to physical components."

This observation is particularly relevant to a modular environment where design decisions need to be made regarding the constituent elements of a module and the overall function of a module (Yin et al. (2014).

Ulrich provides further elaboration of product architecture by stating that it should include reference to (i) the arrangement of functional elements (ii) the mapping from functional elements to physical components, and (iii) the specification of the interfaces among interacting physical components. Observing the importance of product architecture decisions, Fetzinger and Lee (1997), stated that within a modular context it is necessary to rethink and integrate not only the design of products and processes but also the configuration of the entire supply network. Thus, modular production in a supply chain setting moves beyond traditional in-house applications of modular production to the management of module design, production and assembly across those suppliers adding value outside the focal organisation (Doran, 2003). This said, Shamsuzzoha & Helo (2017) found that despite the importance of design modularity, there were few widely accepted guidelines re available for the design engineers and this may have subsequent consequences for changes to design made module or sub-module suppliers.

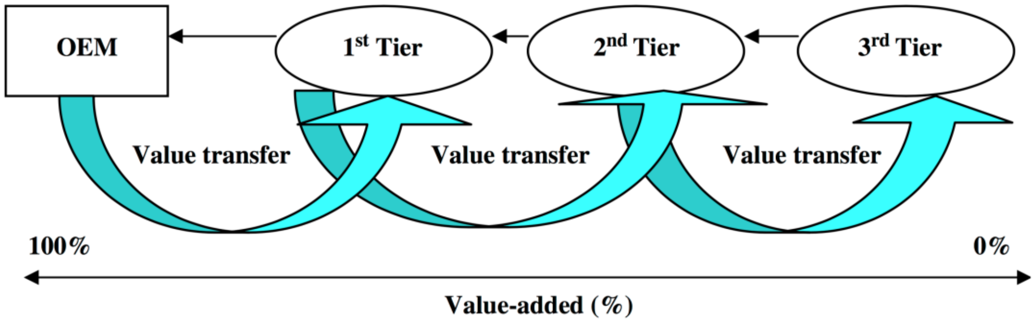
2.2 Supply chain and Logistics perspectives of modularity

Howard & Squire (2007) sought to examine under what conditions modularity leads to increasing [supply chain] collaboration and concluded that supplier relationships are necessarily mediated by specific assets and the degree of information sharing. The focus on who does what in a supply chain delivering modular solutions is eveident in much of the research in this area and is influenced by product architecture decisions made at the outset of the modular journey. In their review of research relating to product architecture and supply chain design, Pashaei & Olhager (2015) found that decisions relating to product architecture strongly influence the subsequent design of supply chains providing modular solutions and that careful consideration should be given to the supplier selection. Similarly, Ülkü & Schmidt (2001) observed that module design and product architecture has an impact upon the nature and scope of relations with module and sub-module suppliers who will become responsible for articulating the design requirements of the module customer. For a module supplier, the arrangement, mapping, and interface elements of the module must accurately reflect the specific, and often demanding, needs of the OEM customer and must provide integral variety that can deliver a wide variety of options for the final consumer. Novak & Eppinger (2000), adopting a property rights approach, suggested that in house production of complex products should be undertaken in-house since externalising operations (for example, outsourcing of complex modules) has a negative impact upon the development internal skills and knowledge development

However, Hsuan (1999: 39) observed that modularity (whether procured externally or provided internally) provides “the opportunity for mixing and matching of components in a modular product design in which the standard interfaces between components are specified to allow a range of variation in components to be substituted in product architecture.”

Standard interfaces subsequently led to “partitioning” which accommodates the various value adding activities of manufacturing, design and logistics tasks required to produce a module can be decoupled and produced outside the focal company (Baldwin & Clark, 1997, 2000). This partitioning has the potential to determine the distribution of power within the firm, as well as communication channels within the supply chain and the division of labour (Henderson and Clark, 1990).

For suppliers, the transfer of value from the OEM is not only necessitating significant changes to the strategies, scope and focus of module suppliers, but is also causing such suppliers to reorganise their own suppliers in an effort to ensure the smooth flow of modules to their customers in a cost-efficient manner. In this regard, Nepal et al. (2012) emphasised the importance of integrating product architecture decisions with manufacturing and supply chain decisions during the early stage of the [module] product cycle. Specifically, the authors observed the following potential supply chain affects: (i) Outsourcing and transfer of more components to upstream suppliers, (ii) consolidation of first-tier suppliers into mega module suppliers, (iii) the reorganisation of value creation activities where some former first-tier suppliers become value-added second-tier suppliers (Doran, 2003, 2004), (iv) suppliers become more powerful and increase their bargaining power because of the large role as a module supplier, and (v) the formation of more strategic alliances/partnerships between OEMs and their suppliers. Furthermore, as value is transferred from the OEM to a module supplier there is a tendency for suppliers further up the value creation chain to refocus their own operations and to transfer non-strategic value to their upstream suppliers. This transfer of value necessitates a change in the logistics operations environment and requires a redrawing of logistics operations. In essence, the modular approach involves the transfer of value from customer (the OEM) to a supplier (referred to here as the Module supplier) and necessitates a degree of value transfer activity as the focus of each actor in the supply chain realigns it operations to the modular environment (Figure 1). Figure 1 – Value Transfer Activity



Source: Doran et al. (2007)

This transfer of value appears, on the surface, a straightforward exercise in managing suppliers and establishing design rules that suppliers (specifically, Module suppliers) can accommodate. However, the focus of prior research has not clearly determined the characteristics of key players in a ***single supply chain*** delivering a complex module on a just-in-time basis and reflecting a myriad of customer options in a synchronous supply environment.

Value transfer also has an impact upon the operations of logistics providers. Van Hoek and Weken (1998) observed that modular production requires a further product re-design, involving not only the internal production process but aiming at a further involvement of suppliers in the inbound and the outbound flow of goods which makes it possible to further involve both distributors and suppliers in the manufacturing process and create a new tier of suppliers. Furthermore, the authors suggest that the expected benefits of the increased (physical) integration in the inbound and the outbound flow of goods are increased responsiveness to customers and increased efficiency. In this regard, Pekkarinen and Ulkuniemi (2008), noted that Logistics service providers (LSPs) act as the link between the manufacturer and its customers and suppliers. This role creates many challenges for logistics firms, as they are required to understand, design and manage new customer-oriented services and logistics solutions for the total supply chain of their customers. Logistics in a modular context is a key service element and takes on increased importance where modules and parts for modules are delivered both on a JIT and a Just-in-sequence (JIS) basis. Fredriksson (2006) urges caution by suggesting that the modular approach requires extensive coordination with all elements of the supply chain and particularly logistics providers who will be expected to manage the customization requirements offered with modules. This has resulted in what Bask et al (2010) term Value-added Logistics centres (VAL). Such centres facilitate the enhanced coordination requirements required for modules and the need to ensure that customized modules are delivered just in time and exactly to customer specification.

2.3 Operational perspectives of modularity

Once the design decisions have been made, suppliers selected and logistics providers secured, it is necessary to understand the impact that modular provision has upon module operations,. In this regard, Sako and Murray (2000: 4) describe operations modularity as 'modularity in production' which they define as "the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then brought onto the main assembly line and incorporated through a small and simple series of tasks." Gershenson et al. (1999) found that modular production allows a designer to control the degree to which changes in operational processes or requirements affect the product and, by promoting interchangeability, modularity gives designers more flexibility to meet processes changes. To accomplish this, the overall design task has to be divided into smaller tasks and the interface between them should be properly defined; this accommodates the re-use of existing designs with only minor changes to the modular architecture, reducing the time and effort needed to upgrade an existing product (Sosale et al., 1997). For modularity in production to function efficiently it is important for the module supplier to effectively manage a complex range of requirements, so that the potential benefits of modularity are accrued. In this regard, the seminal work of Ulrich and Tung (1991) stated that the operational benefits of modularity include (i) component economies of scale due to the use of components across product families, (ii) ease of product updating due to functional modules, (iii) increased product variety from a smaller set of components, (iv) decreased order lead-time due to fewer components, (v) ease of design and testing due to the decoupling of product functions, and (vi) ease of service due to differential consumption. Feng and Zhang (2014) note that the modular approach differs from the traditional approach to production in two distinct aspects: firstly, operational decisions regarding the sourcing of multiple components are centralized in the hands of a single module supplier, and secondly, a portion of the assembly job is transferred from the final stage to the upstream stage, therefore, the production time at the final stage is reduced. The key issue for modularization according to Ernst and Kamrad (2000) is to design for efficient linkage mechanisms in the constituent units so that any required combination can be conveniently assembled. Subsequent research by Kamrad et al. (2013) observed that 'modularity in design' and process modularity corresponds to 'modularity in production.'

In essence this view seeks to make the link between the strategic decision to adopt modular design and the subsequent impact that such a decision has upon the operational processes required to articulate modular production. Lampón et al (2017) observe that from an operations management perspective, the modular platforms adopted by automobile manufacturers will lead to improved network capabilities; specifically, those that stem from the coordination of manufacturing plants in the network. A summary of the four modular perspectives explored in this review and the influence that value transfer has upon such issues and decisions is shown in Table 1.

Table 1 - Multi-dimensional modular design decision framework

Dimension	*Modularity*	*Value transfer issues*	*Sources*	*Decision dimensions*
1	Design perspectives	Architectural issues	Ulrich (1995); Nepal et al (2012)	Design options impact; availability within supply chain
2	Supply Chain persepctives	Measuring impact of modularization (Suppliers perspective) Just in sequence of modular sub-assemblies and complete modules	Henderson and Clark (1990) Sako and Murray, (2000) Ernst & Kamrad (2000) Van Hoek & Weken, (1998) Bask et al (2010) Fredrikson (2006)	Modular production communication with upstream suppliers and downstream customers Technological impact Increased need to add value
3	Operations decisions	Organisational layout, design and processes associated with modular production	Baldwin & Clark . (1997); Ernst & Kamrad (2000); Hsuan, (1999)	Layout process changes; Communications; Training requirements.
4	Logistics perspectives	Delivering completed modules on a synchronous basis	Doran (2004)	Value transfer activity is evident in the transfer of module movement to specialised logistics providers that can add value in terms of synchronous delivery as well as the management of parts coming from sub-module suppliers

Research into modularity is largely influenced by the papers detailed in table 1 and referred to in an extensive literature review conducted Dörbecker, Böhm & Böhmann. (2015)) (). Whilst such papers have assisted with creating a clearer understanding how modularity works at the organizational level few have sought to examine the impact that modularity has upon the key value-adding activities within a modular supply chain.

This paper seeks to address this gap by examining the impact that a modular approach has upon three value-adding operations within the key value adding areas of a supply chain supplying module solutions for a UK-based OEM.

The decision to adopt a modular approach to designing, building and coordinating module production and processes has implications for where value is positioned in the supply chain and how value creation and value transfer should be coordinated and controlled. Whilst the concept of modularity and its constituent elements (architecture and interfaces) has been broadly defined the construct of value transfer activity within this modular context is less visible in the existing literature. We therefore seek to explore the dynamics of value transfer activity within the context of a modular supply chain so that a clearer understanding of the construct can be achieved. This modular supply chain is focused on the cockpit module for a single UK-based OEM. Since module design impacts process issues both within the focal operation and within the supply chain the following research question has been developed:

What is the impact of modular design on the supply chain configuration and the value-adding processes of key actors in a modular supply chain?

3. Method

This study explores the provision of a module using semi-structured interviews and documentary analysis of the outsourced provision of cockpit modules and the impact this has on the operation of the case organisations (Cassell and Symon, 2004, Yin, 2003b). The cockpit module was selected because it is one of the most complex module in a car and represents an array of parts and systems. Managing this complexity is a difficult challenge but the potential benefits associated with adopting a modular approach are significant.

Following insights developed by Benbasat et al. (1987) and Eisenhardt (1989) the cases and respondents were theoretically sampled from leading manufacturing organisations in the automotive manufacturing sector that were assumed to exhibit typical or representative practice.

Respondents within the case organisations were expected to demonstrate a 'polar' range of reactions based on their perspective, as buyers or providers, within the supply chain providing valuable insights relating to the supply chain implications associated with the provision of modular products (Bethlehem, 1999, Yin, 2003a).

Experts were selected from a single OEM manufacturer in the UK based on their substantive experience within the research area of cockpit development and their ability to provide the specific information required (Maxwell, 1997).

The sample consisted of staff in production, procurement and design, and who have worked within their organisation in the specific role for at least two years, and who were actively involved in resourcing decisions related to the production of the cockpit module.

Data collection was undertaken between January and April 2016 and consisted of a thorough review of secondary industry documentation and extant research to sensitise the researchers to the key issues and themes. Secondly, a series semi-structured interviews with industry experts were undertaken. The interview questions were derived by thematising the research question into meaningful sentences that allowed the respondent to describe the events in their own terms and language (Kvale, 1996, Kvale, 2007).

3.1 Data Acquisition

Interviews were conducted with 15 respondents representing each of the organisations involved in the provision of the cockpit module (Table 1)

Table 2 - Respondents

OEM	Module supplier	Sub-module supplier
Buyer of the cockpit module 6 respondents	Manufacturer of the cockpit module 7 respondents	Provider of the Heating, Ventilation and Air conditioning module (HVAC) 2 respondents

All documentary evidence, interview notes, diary and research log notes were entered into a password protected database NVIVO 10. Critical incidents (Chell, 2004) were also requested, for example, returning module production in house, to explore examples of how performance may be positively and/or negatively impacted by such events. There are of course a number of issues regarding the nature of the data collected during expert interviews, particularly around problems of agreed language, available constructions, discursive tactics, and presentational bias especially within a commercial setting (Dingwall, 1997).

We used a purposive sampling approach designed to 'generate a sample that will address (the specific) research questions' with careful attention to any included biases during the research (Kvale, 2007, Teddlie and Yu, 2007: 84). Validity (or quality) of the research was assessed through criteria suggested by (Klein and Myers, 1999, Stiles, 1993) as they particularly suit realist interpretive positions. Finally, to maintain anonymity all original respondents are referred to by role within their organisation categorised as either 'OEM or 'Suppliers' of modules.

3.2 Data Analysis

Systematic Thematic Analysis following Guest et al. (2012) was applied and focused on themes emergent from the description of the events and activities occurring around the processes of modular design and implementation (Beech, 2010). The initial sensitising framework was based on the literature (table 1) and on the measurement framework of Panlou and Sawy (2011).

This organising framework was used to guide the interview and subsequent analysis and emergent themes within and across subjects and organisations identified. In this part of the analysis, emergent themes in the transcripts were open coded and named at nodes based on the literature for example: 'sensing', 'integration and relational ', and 'coordination'.

Coding was initially targeted at these nodes, and across organisation type (OEM/Suppliers), thereafter expanded out as analysis proceeded then axial coded to re-aggregate to final theoretical themes.

Each interview respondent was coded as a case node, classified, and then on-coded to the framework. Coding initially was based on the themes identified earlier from secondary documentary evidence and the literature research then this initial frame was adapted, laddering up and down through the themes, as the analysis proceeded and further insight was gained from our respondents. Coding continued in this way until we converged on the final themes by a process of constant comparison, using framework matrices and iterating between the raw data with that already encoded and by this means arrived at the final breakdown used in the analysis.

4. Findings

Four distinct themes were developed in our review of the literature and extracted from the analysis (Table 1). A sub-section introduces the extracted theme and shows the link from the respondent empirical data, for both OEMs and Suppliers (including both the module supplier and supplier of sub-modules to the module supplier), via a summary construct to the dimension (shown as tables 2 to 5).

4.1 Design related findings

We observed two main aspects in this dimension - firstly, module design control and the location of critical resources shifts away from the OEM towards the tier one supplier, and secondly a dependency risk emerges between the OEM and their suppliers. Focussing the OEM perspective, the decision to adopt a modular design strategy, in principle, enhances their ability to focus on the final assembly process, gain access to potential savings, and offer high variety and volume in terms of mass customisation. However, whilst gaining access to resources outside of their organisational boundary (by outsourcing the cockpit module), it exposed a new dependency risk, since competence in design and manufacture moved from OEM to the module , who then assumed more risk and enhanced value creation capability.

> *"The modular design approach leads to increased quality and flexibility for our new customers [the OEM]. We now supply cockpits to many of the leading OEMs and the learning from each customer informs our overall approach and our ability to take a pivotal role as one of an elite group of global cockpit suppliers." (Module supplier)*

Process expertise in cockpit module manufacturing becomes vested in the module supplier operation, whilst for the OEM, installation of the cockpit module becomes an assembly operation rather than a complex manufacturing and installation process requiring a great deal of supply chain management activity and enlarged warehousing requirements for each part of the product. This makes switching cost very high within a market of limited module suppliers, a situation exacerbated by the tight assembly integration at the OEM site.

In summary, an increase in dependency, loss of internal expertise and competence are distinct feature associated with embracing a design strategy involving the provision of the module by an external module specialist. This transfer of expertise, can act to consolidate and move competence and value away from the OEM towards a tier one supplier; this supplier will then assume a more central role in the supply chain for that high-level module (Table 3).

Table 3 - Design findings

OEM	Module Suppliers	Key observations
"The decision to design for modularity allows us to cope with increasing complexity (mass customisation). Much of this complexity derives from the offerings we now provide our customers, from enhanced functionality to a range of trim finishes." "The module supplier has a range of technologies and manufacturing processes to hand and we do not currently have our own manufacturing capability. It is something that can be a little frustrating as we are reliant on the module supplier and this is sometimes challenging for us."	"We need to keep an eye on market demands and also reduce our product development times. Having a design team with enough technical bandwidth to cope with extreme demands from the OEM is also much more important now that we are responsible for the entire cockpit module" (Module supplier) "The modular design approach offers engineering robustness, repeatability of assembly and quality improvements." (Module supplier) "We can make suggestions for design changes and do; sometimes this result in change to internal architecture but the interface remains the same. We can't change that." (Submodule supplier)	Design for modularity leads to power, control and capability transfer issues
"For us the operation has not become easier and in many ways, it is more challenging. When you transfer the module wholesale there is the concern that you lack real control. It's probably not a real concern but more of a psychological issue."	"The module makes it easier for the operators to pick up the assembly of the cockpit and makes on the job learning much easier. Given the fact that a module supplier is likely to locate close to the OEM, delivery problems are almost non-existent." (Module supplier)	OEM has less need for Supplier Management capabilities
"[The modular approach] has allowed for the development of partnership relationships with shared objectives and goals. " "We do not have to worry about upstream suppliers and increasingly rely on our module supplier to take care of this"	"[A modular design approach] enables the transfer of risk to us as the module supplier. We now do far more of the complex work associated with the module, including design activities, inventory management and sequencing completed units to a JIT environment." (Module supplier) "As a sub-module supplier, we generally just supply what is required by the module supplier and are not too involved in design-related decisions unless they impact our sub-module." (Submodule supplier)	Cost reduction initiatives increasingly the remit of the module supplier
"It's all about cost effectiveness and reducing these costs continually. Modules are more expensive to make but more cost effective in terms of assembly processes." "If we can cut out cost by transferring module production to a module supplier then this makes financial sense of for us. This is what designing for modularity is all about."	"It's cost effective due to transferability of component parts to other cockpit modules." Module supplier (Module supplier) "For us we are always being asked to look at ways to reduce our costs. We used to have OEM staff assist cost reduction but now it's more the Module supplier. (Submodule supplier) "Whilst there is some potential for reducing costs the module that we supply is difficult to change as design is imposed for a period of time, normally a year or 18 months." (Submodule supplier)	Transferring module responsibility reduces costs for OEM Cost reduction initiatives become the responsibility of the module supplier
"[A modular approach] leads to total control of the business and provides the ability to ensure all parts are functional and reduces costs related to warranty claims. " "…This is probably a natural extension of our decision to seek a module supplier that can deliver completed modules to us without any quality problems and is one of the key benefits of designing for modularity."	"For us the biggest challenge is improving quality, improving processes and responding quickly and flexibly to OEM demands within the module design constraints." (Module supplier) "It's important for us to deliver exactly what's needed [of the module supplier] and to make sure that we can adjust our capacity to change volume when this is required. It does happen and we have enough spare capacity to deal with late changes." (Submodule Supplier)	Quality and process improvement initiatives become the responsibility of the module supplier

4.2 Supply chain related findings

A natural consequence of the decision to adopt modular solutions is that the product moves from being sourced and built within the OEM operation to being sourced externally. The results of our interviews indicate, that from the OEM perspective, the supply chain decisions focus, primarily, upon ‘soft issues’, such as dyadic relationships to improve visibility, coordination for inventory management and joint initiatives for achieving enhanced performance. Overall, the OEM focus is on the challenges associated with the lack of visibility and the benefits accrued from the reduction in supply chain complexity. In terms of suppliers (both the module supplier and the sub-module supplier), they are keen on achieving greater levels of integration, reducing cost during demand uncertainties and defect reduction during batch production switching. Furthermore, the suppliers tended to focus on maintaining dependability and ensuring that the OEM received the modules on-time, in-sequence and to customer specifications (Table 4).

Table 4 – Supply chain findings

OEM	Module Suppliers	Key observations
"It makes it much more of a challenge [since] we do not have as much visibility [of the supply chain]. Also, relying on a key strategic module supplier is a major issue and depends on the robustness of the business relationship, as the supplier is carrying all the risk with warranty etc. In essence, we have been used to providing the module in-house but now it is entirely produced externally and we now need to rely on the [module] supplier's capability."	"It allows for module integration since the supply chain is focussed on modular supply conditions. We have also redesigned what we offer and decided that some of our low value-adding processes are can be more effectively organised by the sub-module supplier. For us it's just a natural progression." (Module Supplier) "We supply the HVAC [a sub-module of the cockpit module] module and now undertake a number of the processes that were previously done by the cockpit supplier. We don't mind since it extends our capabilities." (Submodule Supplier)	Desire to improve visibility Integration and inventory management become critical Evidence of Value transfer activity
"All supply is now direct to plant rather than via several supply routes. This makes the coordination of the supply chain much less complex. For us this reduces the previous levels of complexity in terms of parts management and accommodating stock on site; it's a real benefit of transferring the value to the supplier." "In essence, much of the day-to-day management of the supply chain is the responsibility of the module supplier and we simply expect them [the module supplier] to deliver to our requirements."	"Theoretically, it should make it more cost effective but sometimes that is not always the case as unexpected costs arise." (Module Supplier) "We are sometimes pressured by the cockpit supplier to think about our production processes with a view to reducing costs. Its [cost reduction mentality] now part of our DNA." (Supplier to Module supplier)	Coordination less complex for OEM Operational and SCM now handled by the Module supplier
"There is a greater focus on delivering sustainable and environmental solutions. We need our supplier to engage with us on initiatives to become more sustainable and this means getting rid of waste. "The supply chain needs to adopt a different approach to logistics, i.e. increase their downstream JIT capabilities. We are aware of our supplier transferring some of its production further upstream and they need to be aware of extending the sustainability initiatives to these suppliers."	"If the OEMs build is compromised by another supplier as the OEM could swing from an 80% left hand drive build to an 80% right hand drive build, with only 2hour stock levels it's difficult to switch. With the traditional [non-modular] approach we tended to have cushion stock." (Module Supplier). "The modular supply chain has to be well organised and coordinated to avoid letting the customer down. This all has to be done without mistakes as most of what we supply to the OEM is customized." (Module Supplier)	OEM waste reduction focus increasing and now becomes the responsibility of the Module supplier

4.3 0perations related findings

A modular approach involves transferring value-adding activity to a module supplier and has a significant impact upon day-to-day operations management activity. In essence, module suppliers are required to provide cockpit modules in sequence and to customer specific requirements (accommodating the myriad of options made available to the customer by the OEM). The outcomes of our interviews indicate that clear processes need to be in place for ensuring that any changes, especially in module interface requirements, and that such changes are communicated and agreed with the module supplier as even minor changes can severely impact operations. Deploying the manufacturing operation for cockpits across the supply chain involves standardisation of tooling and processes at the site of the supplier and integrated change procedures. Common platforms and tooling emphasise a design approach focused on assembly and product integration. This implies assembly at the supplier becomes tuned and specified towards OEM design and production demands and is a form of relational investment that deepens supplier/buyer integration and adds to switching cost risk.

A summary of interview responses is presented in Table 5.

Table 5 – Operations-related findings

OEM	**Module Suppliers**	**Key observations**
“The production (design) element is no longer an internal issue and we have now reduced the complexity of our own operations. We used to do a lot of this but now we focus on the overall design of the module.”	“Depending on [the] vehicle architecture, it should not make much difference. If anything, it allows for more complexity/customization.” (Module supplier)	Focusing on the design of the module.
Much of the value comes from our [module] supplier who controls upstream supply and the logistics activities involved in making sure that all parts for the module (particularly sub-modules) are available.”	“Previously the cockpit [module] was assembled inside the car, with modular cockpits it’s easier as the cockpit is assembled outside the car. This leads to much improved assembly operations with better quality and lower cost.” (Module supplier)	Managing and developing suppliers Involving suppliers in design for modularity
“As a project engineer it makes it much more challenging and complex, since much of the work is conducted outside our company.” On the whole, the managing of our module supplier is smooth but we still have some issues further up the supply chain which we can generally sort out but increasingly we do this via the module supplier”	“Our customer requires quite a complex module and we as the module supplier have to ensure that we do not make errors.” (Module supplier) Cockpits can be made more quickly than before with training also becoming easier due to the repetitive nature of assembly.” (Submodule supplier)	Usage of standard critical parts across various modules Trust and confidence of supplier
“We need to think more carefully about designing parts for modular use rather than thinking solely about designing independent parts.” “The decisions we make here have significant impacts on the whole supply chain and we need to make sure that we communicate design changes to suppliers.”	“The design of the cockpit was based on the OEMs design so that all options could be built around a base unit. So, this allows us to offer lots of options within the same module.” (Module supplier) “In our design, the same part was used for two different vehicles from the basic cockpit up to the cockpit with the full complement of options (satellite navigation etc.).” (Module supplier)	Standardisation and design for modular quality
“It’s business as usual and this module is just the same as any other of our modules that we have outsourced for a number of years. We have plenty of experience and trust our module supplier.”	“It simplifies vehicle assembly. Cockpit assembly itself has to consider all parts and systems as self-contained and needs to consider how all parts and sub-systems can be quality checked, either at the end or during assembly.” (Module supplier) “The impact is positive as it provides a repetitive process for the operators to follow. With [our] pick by light systems the parts are picked from lineside racks in the correct sequence at the correct station, to minimise build issues.” (Module supplier)	Competitiveness and unique value propositions
“The operations have to change in order to cope with extremely complicated and multi-discipline part assemblies. We have pushed most of the operations to our module supplier and we simply install the cockpit, which takes about 90 seconds! “… It also means that we don’t need space to store cockpits and can use this space for more productive activities.”	“From our viewpoint, it means that multi-platform assembly lines and common tooling strategies are possible, making the process less complex and less costly. Before we went modular the main wiring harness from the entire cars was on the cockpit, now as the cockpit is a module it’s simply plug and play.” (Module supplier) Our part is simple to fit into the [cockpit] module because all the decisions regarding interfaces were decided well in advance of production. There are always issues but these are less complex for the modules that we supply parts for. For dashboards that are non-modular we tend to have more operational problems and this can cause disruption to our operations.” (Submodule supplier)	Simplification and pool proof methods

4.4 Logistics related findings

Van Hoek and Weken (1998) suggested that modular design must incorporate the potential increased role of suppliers involved in the provision of inbound and outbound movements and that these suppliers could be key to capturing the cost benefits associated with a modular approach. Respondents were therefore asked to comment upon the role of logistics suppliers for the provision of the cockpit module (Table 6).

In terms of coordinating mass customization, connectedness with the OEM and with upstream suppliers takes on a more significant role within this modular environment and necessitates the ability of the Logistics provision to translate the often-complex requirements of the OEM into sequenced, JIT deliveries. The module supplier is charged with managing this complexity and has had to ensure that its Logistics capabilities are sufficient for this modularisation task.

Table 6 – Logistics related findings

OEM	Module Suppliers	Key observation
“Logistics now has to be able to manage customer inbound digital ordering systems, be able to break these demands into individual supply chain demands, then deliver these parts in sequence to the line, then the final assembly to the OEM. It allows a simple Just in sequence logistics chain for the cockpit which, in turn, allows for reduced logistical space.”	“Theoretically, the modular approach should make the logistics process easier, as the OEM will give a forecast that provides an overview going forward maybe 12 months. This can then be broken down into monthly/weekly/daily schedules for the Supplier, and therefore daily/hourly deliveries into the assembler can be adopted and Just in Sequence process is pushed out to the supplier base.” (Module supplier) “As the module supplier, the logistics service has to be synchronised to the specific requirements of the customer without any errors. This is a real challenge and one that has required a great deal of effort and change to our operations.” (Submodule supplier)	Digital ordering and receipt of goods Accurate Scheduling and forecasting
“For us, it involves a reduction in the movement of the number of parts. We offer lots of variety for the customer but we are always looking to improve how we offer this variety; if we can reduce complexity through smart Logistics solutions then that is what we do.”	“With a lot of the parts being crossover over a number of different variants the hardest part is making sure there are enough of the finishers (vents, glovebox lids etc.) of the correct colour/variant to cover the build.” (Module supplier) “The main issue with the modular approach is making sure there is enough stock to cover the build. If we do not have sufficient stock then the OEM may need to stop assembly. (Submodule supplier)	Demand visibility Usage of technology to reduce complexity Managing standardised common parts
“Several modules can now integrate different car models; better JIT process and the components from the cockpit are also modules which makes the logistics function far less complex. It reduces line side complexity, improves packaging density, and maximises line side space resulting in greater value-added operations.”	“It puts more pressure on the Logistics operation due to the smaller stocks being held both lineside and in the warehouse. Logistics is the key element in keeping the line running at the required Takt time to supply the OEM.” What has changed [as a result of supplying to a module] is that we don’t supply to stock. Much of what we do now is synchronous as our module can be tailored to the requirements of the customer.” (Module supplier) “Most of the time the logistics function is able to translate production into OEM requirements without error. This said, we have had to seriously up our game to make sure that modules are delivered synchronously and without error or delay.” (Module supplier)	Materials management and novel methods Order batching versus. productivity

5. Discussion

The review of the literature identified that modularity was an approach to designing and producing products, which accommodates mass customization and ease of assembly at an affordable cost. The inherent logic of modularity is easy to follow and is now gaining popularity in high volume production environments. The key focus of this research has been to explore the impact of modular design on the supply chain configuration and the value-adding processes of key actors in a modular supply chain. This approach was deliberate since it is at this stage of the OEM-Supplier engagement interface where much of the impact of the decision to adopt a modular approach is likely to be manifest and where the key dimensional decision areas of design, supply chain, operations and logistics activities will reside.

We found evidence to support the value gains commensurate with mass customization, particularly with regard to the ability of the OEM to offer its customers an increased variety of cockpit options (Starr, 1965; Baldwin & Clark, 1997). During factory observations, the Module leader for the OEM stated that 80% of the cockpits being fitted were customer-specific and could not be fitted in any other vehicle. This level of optionality provides challenges for each element of the supply chain and necessitates the type close supplier integration observed by Howard & Squire (2007), particularly with regard to the need to offer specific [modular] assets and information sharing activities.

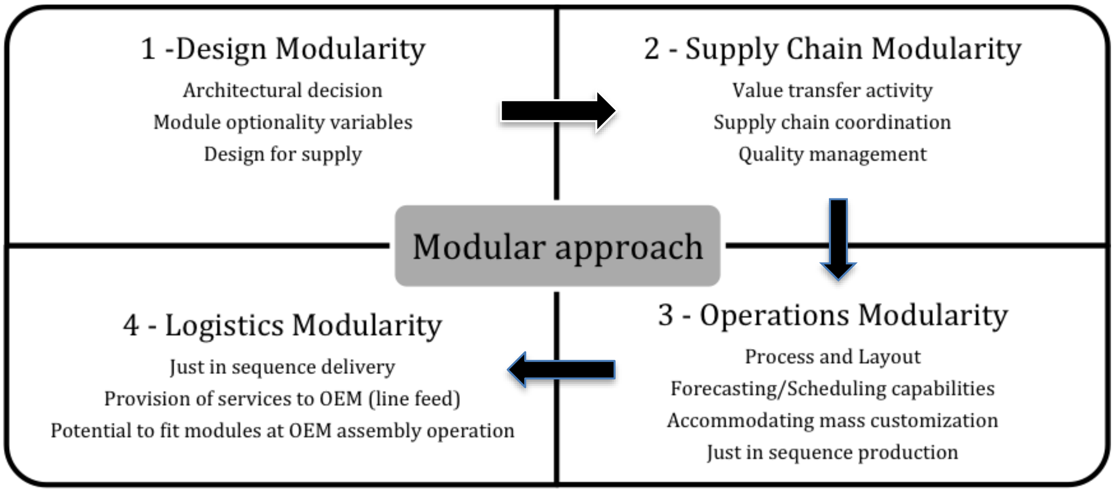
With regard to module architecture (Ulrich, 1995; Nepal et al, 2012), the findings indicate the need for clear articulation of module function, mapping and interface in each of the case operations. Whilst much of this activity was OEM-focussed, the module supplier observed that they have the capability to play an increasing role in the design decisions and this may lead to power and control issues in the long-term. In terms of 'production modularity' (Sako & Murray, 2000) the research found this description to be an accurate reflection of the way in which cockpit modularity operations are arranged and operationalized. Furthermore, the research observes that each of the suppliers involved in providing parts for the module and for providing the complete module, do so to a high degree of accuracy and to a just-in-sequence delivery protocol. This ability demonstrates the enhanced abilities of these operations and the evolved nature of supply chain management in a modular context.

A contribution to knowledge derived from our research is the development of 'Key dimensions of modularity' that influence the modular approach (Fig 3). Such dimensions are likely to be evident in both production and service environments, particularly where OEM operations seek modular solutions in partnership with established module suppliers The "Dimensions of Modularity" commences with the Design decision (Design Modularity), which establishes rules for current and future module iterations and for communicating these decisions to key members of the modular supply chain. In the first instance, the Design

Modularity element is likely to involve close ties between the OEM and the Module Supplier design teams; subsequent design cascading may be managed by the Module Supplier and its upstream suppliers. Turning to stage 2 – Supply Chain Modularity –will focus upon ensuring that the module and its sub-modules are delivered on a just in time basis so that the benefits to the OEM can be fully realised (customized modules and zero stock in the OEM). In addition, the module supplier will take on a number of roles, including the coordination of upstream suppliers involved in providing products and services related to the module and ensuring the quality management of these inputs and the optionality built into the module. Dimension 3 - Operations Modularity - follows naturally from the first two stages and reflects the need for the operation to be designed to accommodate the mass customization requirements associated with the module. As this research has found, the cockpit module presents the need for the module operation to fully and accurately articulate the forecasting and scheduling data received from the OEM and to operationalize these requirements without error and reflecting customer optionality. In essence, for the OEM, the operations change from a high level of involvement in both manufacturing and assembly to a pure assembly operations environment. The OEM benefits from space savings since the module are delivered synchronously by the module supplier for each day's production. Furthermore, the amount of time spent installing the module is just over 70 seconds. For the module supplier and suppliers of sub-modules, the necessity to manage the stock, manage the assembly and to accommodate synchronous supply is key elements of modular supply.

Stage 4 – Logistics Modularity - involves the outputs of stage 3 and is a key element of the modular approach. The Logistics provision for modular solutions seeks to ensure that modules are delivered in sequence and just-in-time to match the daily shift operations of the OEM. There is no space at the OEM to store modules and each module is sequenced to be fitted very soon after delivery. This means that the Logistics element is key to the success of modular operations and accommodates the requirement of the OEM to have zero stock of cockpit modules at the end of each shift.

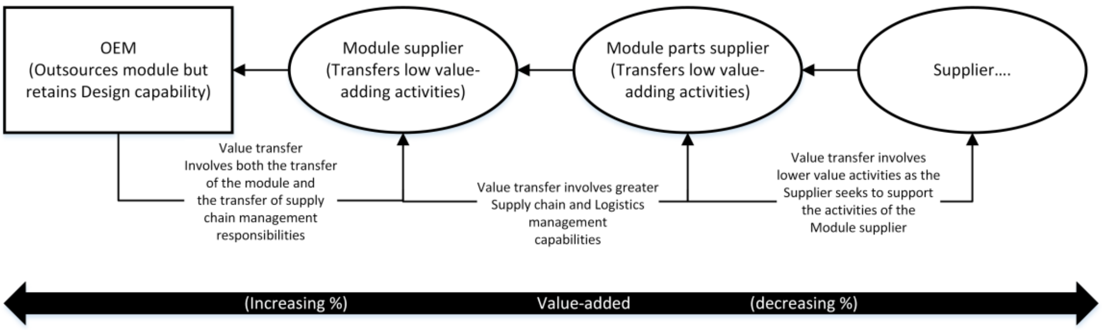
Figure 3 – Dimensions of Modularity



Source: Authors

The issues depicted in figure 3 detail the multi-dimensional decision areas and the impact that these areas have upon both the OEM and the module supplier. In essence, modularity in production (Kamrad et al., 2013, Sako and Murray, 2000) is a combination of modularity in design and modularity in process, and has an impact upon decisions relating to where value is located in the modular supply chain. Drawing upon the observations of Doran et al. (2007), the findings suggest that the design decision not only impacts the nature and scope of the modular supply chain but also leads to reorganisation of value transfer activity (Figure 4).

Figure 4 – Value Transfer Activity



Source: Authors (adapted from Doran et al, 2007)

The reorganisation of value commences with the decision of the OEM to outsource production of the module. For this research, the OEM was responsible for the module design and sought to retain control of this element. In outsourcing the module the OEM transferred much of the supply chain and logistics management activity to the module supplier.
For the module supplier there was evidence that indicated that they too transferred value upstream to their direct supplier (in this case, the sub-module supplier) in order to better focus upon the need to become more involved in managing suppliers and for ensuring the synchronous delivery of mass customised modules.

Where previous research has examined many of the issues, challenges and benefits of the module approach, there has been little research exploring the operational dynamics associated the value transfer activity. This research has demonstrated that the first aspect of value transfer activity commences with the decision of the OEM to seek external providers for distinct modules and that this transfer of value has implications for suppliers further up the supply chain and necessitates the transfer of skills commensurate with the transfer of value.

6. Conclusion

This study has sought to shed light on the operations associated with modular production and supply and has demonstrated that the decision to adopt a modular approach is one that has significant implications for key players in the supply chain. However, for modularity to be successful it is important to engage key elements of the supply chain when making design decisions for the initial module and for subsequent design changes. Furthermore, providing modules is complex and the issue of complexity was raised in all parts of the supply chain and manifest in a number of ways. For the OEM, the transfer of the module to a Module supplier added complexity to its operations and reduced visibility. For the Module supplier, their enhanced role in the module supply chain required additional capabilities, particularly with regard to accommodating the flexible requirements of the OEM whilst ensuring no disruption to its own operations and those of its upstream suppliers.

Whilst there was no direct reference to value transfer activity (Doran, 2003) there was reference to the enhanced role played by suppliers and the greater technical capabilities required of both the Module supplier and key upstream suppliers. Modularity as an approach to managing cost and offering customisation on a large scale is likely to grow and the emergence of global module suppliers that supply modules to a number of OEMs is a clear indication of this trend.

6.1 Managerial implications

Modularization as a management approach is complex and involves changes to the responsibilities and scope of not only the OEM but also the module supplier and suppliers delivering sub-modules. This is where the majority of the value creation activity takes place and where much of the disturbance of modularity is likely to reside. In essence, each of the parties involved in the modular supply environment need to understand the necessity for greater connectivity at the OEM-Module supplier interface (particularly addressing the need to ensure a clear understanding of the dynamics associated with modular production and supply) and to understand the implications associated with changes to operations, supply chain and logistics management. This research indicates that modular supply is not simply about the OEM/Module supplier interface but extends further upstream to the sub-module level. For those suppliers seeking to extend their activities from a sub-module level to complete module provision it is important to understand the extensive responsibilities associated with this dynamic and comprehensive environment and to fully understand the need to develop both the assembly and supply chain management operations.

6.2 Limitations and future research directions

This research has focused on a single supply chain in the automotive sector with a view to determining the operational dimensions associated with the production of a high value module. In doing so, the research explored the operations from the OEM, the module supplier and a supplier of sub-modules to the module supplier. It is therefore important to determine whether the findings presented in this research are applicable to other module environments, which require mass customization capabilities and which reflect the modularity in production issues explored by Sako & Murray (2000) and which explore, in greater detail, the nature of interface and architectural decisions explored by Ulrich, (1995). This is particularly important where the module contains a number of complex and connecting sub-elements. There is also the opportunity for researchers to extend understanding of value transfer activity in similar modular environments and to extend analysis of value-transfer in a quantitative manner with particular reference to the financial value of such transfer (Doran et al., 2007). A further direction for future research could be to explore the dynamic capabilities associated with module operations and strategies. Teece et al., (1997) described dynamic capabilities as the firm's ability to integrate, build and reconfigure internal and external competences to address rapidly changing environments. The ability to accommodate modular principles and practices requires a clear understanding of the competences that are inherent in the modular supply environment particularly where there is movement of value transfer activity and where such movement shifts capabilities up the supply chain.

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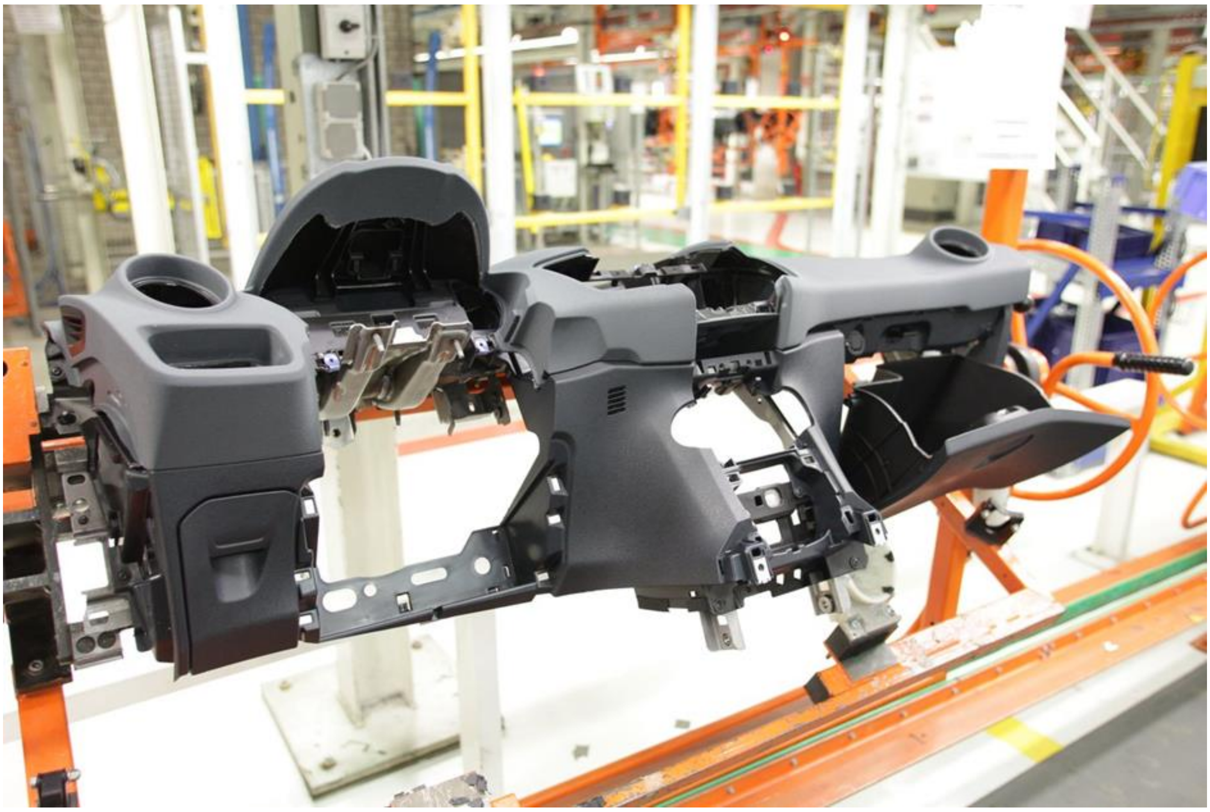
Appendix 1



Source: SAS Automotive Systems