Product architecture and supply chain design: a systematic review and research agenda

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Abstract

Purpose – The purpose of this paper is to systematically review the extant literature on the relationship between product architectures and supply chain design to identify gaps in the literature and identify future research opportunities.

Design/methodology/approach – This paper examines the peer-reviewed literature on product architectures and supply chain written in English. The search strategy is based on selected databases and keywords. In total, 56 articles from 1995 to 2013 were identified.

Findings – Three key dimensions are identified for the categorization of the literature: the type of product architecture, the type of supply chain and the research methodology. Furthermore, we identify themes related to outsourcing, supplier selection, supplier relationships, distance from focal firm and alignment.

Research limitations/implications – The present search strategy may have missed some references that are related to the area. However, as a counter-measure, we used back-tracking and forward-tracking to identify additional relevant papers. A research agenda is proposed for further research on the interaction of product architectures and supply chain design.

Originality/value – This paper is, to the best of the authors' knowledge, the first broad review that investigates the interrelationship between product architectures and supply chain design.

Keywords Product design, Systematic literature review, Platform, Integral, Modular, Supply chain design

Paper type Literature review

1. Introduction

Managing the integration between product architecture and supply chain design is not a simple task for manufacturing firms. An increase in competitive pressures and market globalization is forcing firms to develop supply chains that can effectively manage, on the one hand, product and market aspects such as increasing product variety and customer service and, on the other hand, operations aspects such as cost minimization concerning production, inventories, transportation, etc. along the supply chain. Thus, there is an increasing need from practitioners to integrate product and supply chain design aspects. For example, Volkswagen is adopting a new product architecture with the aim of reaching synergies for its global supply chain (Volkswagen, 2012). As a response to the practical relevance, there has been a growing interest from researchers, in recent years, to study the relationship between product design and supply chain design. Although it is widely accepted that design decisions of products and their associated supply chain are interrelated, it is not clear how they interact with each other (Zhang *et al.*, 2008). In general, little work has been done on the development of decision support models for concurrent supply chain and product design (Chiu and Okudan, 2011), particularly considering the global issues in supply chain design (ElMaraghy and Mahmoudi, 2009). We have been unable to identify any previous literature review on the interaction between product architecture and supply chain design. Therefore, it is both important and timely to review the literature on the interaction between product design and supply chain design. In this review, we focus on product architecture aspects, with particular interest in how modular, integral and platform designs relate to specific supply chain design aspects.

The remainder of this paper is organized as follow. First, we provide definitions of the basic terminology for product architectures, and briefly review previous literature reviews on product architecture or supply chain design. Then, we present the methodology of the review in terms of search strategy and the distribution of articles across journals and over time. We categorize the literature in three dimensions:

1. product architecture type (modular, integral, platform and modular-integral design spectrum);
2. supply chain type (dyadic, three or more stages and general with no specific reference to individual actors along the supply chain); and
3. research methodology type (case studies, conceptual modelling, surveys and mathematical modeling/simulation).

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We identify five thematic findings and develop a research agenda. We hope that this systematic literature review will contribute to the understanding of the interaction between product architecture and supply chain design and that it can encourage new research on this interesting and important topic, with relevance and implications for managers in manufacturing firms. To our knowledge, this is the first broad systematic review taking into consideration the interrelationship between product architecture and supply chain design, including the full spectrum of product architectures.

1.1 Definitions

The product architecture typologies are modular, integral and platform designs, which are defined as follows. Products with modular architecture are characterized by components that are interchangeable, autonomous, loosely coupled, individually upgradeable and have standardized interfaces (Fine, 1998, pp. 134-135; Voordijk *et al.*, 2006, pp. 602). An integral architecture includes components that perform many functions, are in close proximity or close spatial relationship to each other and are highly synchronized, such that a product change made to one component will require changes to other components for a correct functioning of the total product (Fine, 1998, pp. 134-135; Voordijk *et al.*, 2006, pp. 602). Finally, a product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced (Meyer and Lehnerd, 1997, p. 12). Platforms can be related to modular design, in that subsystems or interfaces may be modular in nature or allow for modular add-ons.

1.2 Previous literature reviews on product architecture or supply chain design

Because this study reviews the literature on the interaction of product architecture and supply chain design, we first searched for previous studies on this topic. However, we could not identify any previous literature review on this particular subject. Instead, we could identify ten literature reviews on supply chain design, as well as nine literature reviews on product design; for an overview, see Appendix. The supply chain design literature has mainly focused on the coordination and integration of the production – distribution models, while the product architecture and design literature has focused on product family design through platform-based product development or modularity in the different contexts (e.g. definitions, product, production and organizations).

The interaction between product architecture and supply chain design is not treated in any of these 19 literature reviews; the reviews on supply chain design have not discussed the explicit role of product architecture, and the reviews on product architecture and design have not explicitly treated the relationship with supply chain design. Thus, previous reviews have focused primarily on supply chain design *or* product architecture and design, focusing on a particular aspect or part of the supply chain or one type of product architecture, and not explicitly connecting these two areas in a systematic manner.

2. Methodology

The purpose with this literature review is to summarize the state-of-the-art of research on the relationship between product architecture and supply chain design published in peer-reviewed journals. Literature reviews are important in:

- supporting the identification of a research topic, question or hypothesis;
- identifying the literature to which the research will make a contribution, and contextualizing the research within that literature;
- building an understanding of theoretical concepts and terminology;
- facilitating the building of a bibliography or list of the sources that have been consulted;
- suggesting research methods that might be useful; and
- analyzing and interpreting results (Rowley and Slack, 2004).

In short, literature reviews are important for identifying areas in which further research would be valuable.

In conducting this literature review, the guidelines of Denyer and Tranfield (2009), Rousseau *et al.* (2008), Rowley and Slack (2004), Seuring and Gold (2012), and Tranfield *et al.* (2003) were followed, i.e.:

- locate existing studies;
- select and evaluate contributions;
- analyze and synthesize data; and
- report on the findings in terms of a research agenda proposal.

The broad scope of content analysis can be translated into two levels of analysis:

1. the first level analyses the manifest content of texts and documents by statistical methods; and
2. the second level excavates the latent content of text and documents by interpreting the underlying meaning of terms and arguments (Seuring and Gold, 2012).

Our content analysis process started with extracting and storing the relevant information from the literature in data extraction forms. We used computer-based data extraction forms (in our case Microsoft Excel spreadsheets), which facilitated the construction of summary tables as well as data analysis and synthesis. The extraction form contained general information of the source (author, title, journal and year), product architecture type, supply chain type, relationship between product architecture and supply chain, supply chain stages covered in the research (supplier, purchasing, inventory, manufacturing, warehouse, distribution center, transportation, third-party logistics provider and customers), as well as research methodology, geographical focus, industry, key theme, insights and additional notes. The authors later commenced with full cross-tabulation of the data extraction forms to identify the key dimensions, categories, contributions and themes. The two researchers of the research team have collaborated and interacted frequently on all aspects of this literature review. We followed a double extraction process (Tranfield *et al.*, 2003) with independent assessments and analyses of the material, and later comparisons and reconciliations of the findings when required. By comparing interpretations and findings between reviewers, it is possible to

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minimize errors, resolve any differences and produce a more robust dataset, wherefore it is recommended to employ two or more independent reviewers in systematic reviews (Denyer and Tranfield, 2009; Seuring and Gold, 2012).

The search strategy is based on three selected databases (EBSCOhost, ISI Web of Science, Scopus), which were considered the most relevant databases for our topic. We limited the search to peer-reviewed journals. The selection of keywords was directly linked to the title and topic of the paper. The keywords were grouped in three areas, and all combinations were used. The three groups were:

1 "product architecture", "integral product", "modular product" or "product platform";
2 in combination with "operations", "manufacturing", "production" or "supply chain"; and
3 in combination with "logistics", "transport", "distribution", "network" or "system".

The latter two areas are concerned with the nodes, as well as links in a supply chain or network. For example, one such combination was "product architecture" + "production" + "logistics". The search combinations were applied at the title, abstract and keywords levels, and after sorting out duplicates, 3,170 unique articles were identified. Because the focus of the review is on the relationship between product architecture and supply chain design, we excluded papers that did not include both aspects (i.e. product and supply chain) in the abstract, as well as those that did not explicitly treat supply chain design. The outcome of this procedure was 213 preliminary articles. The research team then made individual content analyses and evaluations before deciding on which papers to include in the review. To minimize limitations to the search strategy and avoid missing relevant sources, we used back-tracking to find earlier relevant sources and forward-tracking to find literature that were referring to the central sources. The result of this procedure was that three articles were added. The final list of papers that explicitly treat the relationship between product architecture and supply chain design includes 56 articles from 1995 to 2013.

3. Descriptive analysis

3.1 Literature across journals

The 56 articles we finally reviewed are distributed among 26 different international scientific journals. Ten journals account for 36 articles (Table I), while the other 20 articles are from 16 different journals. Table I shows that this research area is treated in many different types of journals, including those that focus on business, operations management, operations research and supply chain management. The table shows that some journals focus on particular research methodologies, such as case and survey versus mathematical modeling. The distribution across the four research methodologies is quite stable, ranging between 11 and 17 papers.

3.2 Literature over time

The first paper, identified by this review that covers the relationship between product architecture and supply chain design, is Lee and Sasser (1995) on "Product universality and design for supply chain management". This is a quantitative paper based on a case from Hewlett-Packard (HP) Company, focusing on whether the company should have universal or regional modules to serve markets, using several factors, such as manufacturing and logistics costs for decision support. Two years later, Feitzinger and Lee (1997) studied the HP DeskJet printers relative to mass customization and postponement. In particular, they discussed product, as well as process, modularization and found a strong link between the two. At the same time, Fisher (1997) raised the question: "What is the right supply chain for your product?", linking the type of product to the type of supply chain. He offered a framework, where an innovative product should be managed in a market-responsive supply chain, while a functional product should have a physically efficient supply chain. In terms of product architecture, he proposed that modular products should be managed in market-responsive supply chains. He concluded that "one supply chain does not fit all"; instead, it is necessary to identify the relevant contingencies such as the type of product.

From 2000 and onward, there has been a slow growth in the number of papers addressing the relationship between product architecture and supply chain design. The trend is positive since 1995, growing from one publication per year to five publications in 2012 and 2013 (cf. Figure 1). The number of publications for specific research methodologies exhibits different patterns over time (cf. Figure 1). While case studies, conceptual modeling and mathematical modeling have experienced a rather stable pattern, the increase is largely due to an increase in the number of surveys from 2007 and onward.

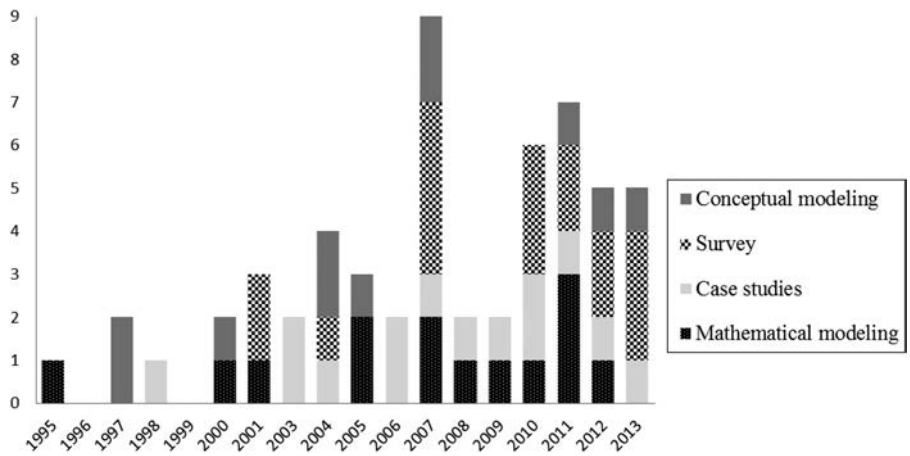
4. Categorization of the related literature

For the categorization of the papers, we used multiple dimensions, such as author(s), title of article, journal, year, product architecture type, supply chain type, research methodology, industry, key theme, geographical focus, supply chain scope (in terms of nodes and links considered from supplier to firm to customer and market) and open comments on particular results and insights. Three dimensions seemed particularly vital for a categorization of the related literature: on the one hand, we studied the interaction between two separate areas, i.e. product architecture and supply chain design, and, on the other hand, different research methodologies have been used to study the relationship between product architecture and supply chain design. From a product architecture perspective, these studies either focused on the full spectrum (i.e. from modular to integral) or focussed on a product architecture type (e.g. modular, integral or platform). From a supply chain design perspective, we categorized the studies as being concerned with general supply chains, dyadic relationships or three or more supply chain stages. The category "general supply chain" was used when the sources did not explicitly mention a particular supply chain (such as dyadic, triadic or other type of supply chain), but it discussed supply chain design in general. Finally, the research methodologies used can be categorized into four groups, i.e. case studies, conceptual papers, surveys and mathematical and simulation models. Based on the above discussion, the authors have done a

Table I Distribution of articles across journals with respect to research methodology

Journal	Case	Conceptual	Survey	Math model	Total	%
IJ of Operations & Production Management	3	–	3	–	6	11
IJ of Production Research	2	–	2	1	5	9
Supply Chain Management: An Int. Journal	2	–	2	–	4	7
Production Planning & Control	1	1	–	2	4	7
Journal of Operations Management	–	2	–	2	4	7
IEEE Transac. on Engineering Management	–	–	2	1	3	5
IJ of Production Economics	1	–	2	–	3	5
Management Science	–	–	2	1	3	5
European Journal of Operational Research	–	–	–	2	2	4
Harvard Business Review	–	2	–	–	2	4
Total top 10 journals	9	5	13	9	36	64
Sixteen other journals	5	6	4	5	20	36
Total	14	11	17	14	56	100
Percentage	25	20	30	25	100	–

Figure 1 Distribution of articles over time with respect to research methodology



three-dimensional categorization (Table II). The product architecture type and the supply chain type frame the table (*y*-axis and *x*-axis, respectively), whereas the research methodology is found in italics in the boxes of the table for each respective source. This classification scheme provides a mutually exclusive classification of the literature, i.e. a paper can only appear in one of the 12 boxes.

From Table II, we can conclude that papers discussing general supply chain issues use conceptual modeling or survey methodology. Conceptual models are only concerned with general supply chains and do not deal explicitly with dyads or multi-stage supply chains, even though the experience and input to the conceptual models may well come from specific supply chains. Case research, surveys and mathematical modeling have been utilized equally for the study of dyadic relationships, while case research and mathematical modeling dominate the studies on multi-stage supply chains. We found that all four methodologies have been used to study the product architecture spectrum, as well as modular designs, while mathematical modeling dominates the research on platforms. It is noteworthy that there no single paper identified in this literature review explicitly treats integral architecture and its relationship with the supply chain design.

5. Content analyses

In the following three sections, we present the content analysis from each of the three dimensions: first, by supply chain type, then by product architecture type and, finally, by research methodology.

5.1 Content analysis by supply chain type

5.1.1 General supply chains

The research on general supply chains typically focus on the importance of integrating supply chain design factors concurrently with product and process decisions and on the role of the evolution of manufacturing capabilities in determining product architecture. The papers that explicitly treat the product architecture spectrum (from modular to integral) are mostly conceptual. For example, Fine (2000) emphasized the importance of integrating supply chain design with product and process development, and suggested that decisions on make/buy, sourcing and contracting need to be made simultaneously with product architectural choices. Furthermore, Fixson (2005) stated that the coordination mechanism across product, process and supply chain is not fully known but that product architecture can serve as a

Table II Three-dimensional categorization of the literature: product architecture type, supply chain type, and research methodology

	General supply chains	Dyadic relationships	Three or more supply chain stages
Product architecture (modular – integral spectrum)	Fine (2000) – *Conceptual* Fixson (2005) – *Conceptual* Yassine and Wissmann (2007) – *Conceptual* Fujimoto (2007) – *Conceptual* Fujimoto (2012a) – *Conceptual* Fujimoto (2013) – *Conceptual* Novak and Eppinger (2001) – *Survey*	Salvador *et al.* (2004) – *Case* Voordijk *et al.* (2006) – *Case* Takeishi and Fujimoto (2001) – *Survey* Hoetker *et al.* (2007) – *Survey* Caridi *et al.* (2012) – *Survey* Baiman *et al.* (2001) – *MMS* Fine *et al.* (2005) – *MMS* Ülkü and Schmidt (2011) – *MMS* Nepal *et al.* (2012) – *MMS*	Doran (2003) – *Case* Doran *et al.* (2007) – *Case* Lau *et al.* (2010b) – *Case* Pero *et al.* (2010) – *Case*
Modular	Fisher (1997) – *Conceptual* Mikkola and Skjøtt-Larsen (2004) – *Conceptual* Krikke *et al.* (2004) – *Conceptual* Feitzinger and Lee (1997)–*Conceptual* Jacobs and Swink (2011) – *Conceptual* Selldin and Olhager (2007) – *Survey* Bush *et al.* (2010) – *Survey* Lo and Power (2010) – *Survey* Jacobs *et al.* (2011) – *Survey* Gualandris and Kalchschmidt (2013) – *Survey*	Van Hoek and Weken (1998) – *Case* Mikkola (2003) – *Case* Dekkers (2006) – *Case* Hofman *et al.* (2009) – *Case* Lau (2011) – *Case* Khan *et al.* (2012) – *Case* Ciravegna *et al.* (2013) – *Case* Lin (2004) – *Survey* Jacobs *et al.* (2007) – *Survey* Howard and Squire (2007) – *Survey* Lau *et al.* (2010a) – *Survey* Droge *et al.* (2012) – *Survey* Salvador and Villena (2013) – *Survey* da Cunha *et al.* (2007) – *MMS* El Hadj Khalaf *et al.* (2011) – *MMS* Chiu and Okudan (2011) – *MMS*	Hong and Hartley (2011) – *Survey* Lee and Sasser (1995) – *MMS* Ernst and Kamrad (2000) – *MMS* ElMaraghy and Mahmoudi (2009) – *MMS*
Platform	–	Lindquist *et al.* (2008) – *Case* Vickery *et al.* (2013) – *Survey* Huang *et al.* (2007) – *MMS* Zhang *et al.* (2008) – *MMS* Zhang *et al.* (2010) – *MMS*	Huang *et al.* (2005) – *MMS*
Integral	–	–	–

Notes: The research methodology is in italics in the boxes of the table; MMS: Mathematical modeling or simulation

coordination mechanism. Trade-off models that are capable of managing higher complexity are required, as some architectural features are beneficial for some processes but can be negative for others, in terms of production and inventory costs. The second major theme includes a group of papers by Fujimoto that have taken an evolutionary perspective when discussing architectural capability. For example, a higher integrative organizational capability in manufacturing would imply a cost advantage when developing a complex and more integral architecture (Fujimoto, 2007). Furthermore, coordination capability, such as the Toyota-style is considered to be more effective in coordinating intensive integral and complex products than for modular products that require less coordination (Fujimoto, 2012a). Fujimoto (2013) took a customer perspective on the manufacturing and product process dimension, stating that price-oriented customers tend to choose modular products, while performance-oriented customers choose integral products. On the other hand, Novak and Eppinger (2001) concluded, on the basis of a survey, that profit-maximizing firms should produce complex systems in-house and outsource products with lower complexity, and suggested that greater coordination between product design and purchasing could improve firm performance.

The research on modular products in general supply chain uses conceptual models or surveys. A specific area of research can be labeled as "Fisher and followers". The starting point is the conceptual paper by Fisher (1997) that suggested that effective supply chains should be designed with respect to the product that is going to be supplied, and suggested that modular products should be aligned with a market-responsive supply chain. Krikke *et al.* (2004) extended this model to

closed-loop supply chains, arguing that reuse on a modular level has economic and ecological potentials. The Fisher (1997) model has also been tested empirically by Selldin and Olhager (2007) and Lo and Power (2010). Selldin and Olhager (2007) tested the framework in a Swedish context and noticed that a match between product and supply chain does not necessarily translate into higher performance. Lo and Power (2010) surveyed Australian manufacturing companies and found that the association between product nature and supply chain strategy, as proposed by Fisher (1997), is not clear. Furthermore, Jacobs *et al.* (2011) studied the effect of product modularity on competitive performance and found that product modularity has a positive effect on integration strategies in supply management, design and manufacturing.

5.1.2 Dyadic relationships

The research on product architecture in dyadic relationships can be divided into two streams: case studies and surveys on supplier integration, and mathematical modeling of supplier selection and location of module product sites. The papers that consider the product architecture spectrum (modular to integral) have mainly been concerned with supply chain configuration between first-tier suppliers and the original equipment manufacturer (OEM). For example, Salvador *et al.* (2004) studied how the supply, manufacturing and distribution network should be configured for different customization levels of the product architectures. They found that suppliers should preferably be small and located near the final assembly plant for component-swapping product architectures. Takeishi and Fujimoto (2001) studied first-tier OEM suppliers and automakers in Japan, and they observed that modular product architectures designed by the OEM were perceived as integral (and not modular) by the component supplier, partly explained by the fact that modules can have an integral architecture *per se*. Thus, the perception of the product architecture can differ depending upon the position and role in the supply chain. Caridi *et al.* (2012) investigated the supply chain choices based on product modularity and innovativeness, and concluded that different kinds of networks are developed for products with high or low degree of modularity. Ülkü and Schmidt (2011) studied the link between product architecture and supply chain configurations using mathematical modeling and found that:

- product integrality is increasing when the scale of market increases due to fixed coordination cost related to integral architecture; and
- outsourcing does not always imply higher modular architectures due to situations when differences in development capabilities between a supplier and a firm are significant.

Nepal *et al.* (2012) studied product architecture strategy and matched it to the supply chain design, and showed that a higher number of product modules present in the supply chain network lead to requirements for higher levels of compatibility (i.e. coordination, information sharing and compatibility in strategic goals).

In an early case study, Van Hoek and Weken (1998) noted that modular products and production can impact the supply chain structure, particularly concerning the inbound and outbound flows of goods. Khan *et al.* (2012) conducted a case study on the relationship between product design and the supply chain and found that alignment positively affected the resilience and responsiveness of the supply chain. Survey studies have primarily focused on supplier integration in relation to modular architecture (cf. Howard and Squire, 2007; Jacobs *et al.*, 2007; Lau *et al.*, 2010a; Droge *et al.*, 2012; and Salvador and Villena, 2013). For example, Jacobs *et al.* (2007) concluded that for maximum impact, product modularity should be implemented with supplier, design and manufacturing integration initiatives. The mathematical modeling papers have mainly focused on supplier selection optimization during the product design stage (Chiu and Okudan, 2011) or optimizing the amount of modules to manufacture at remote sites with respect to manufacturing and logistics costs and meeting the time constraints at final assembly (El Hadj Khalaf *et al.*, 2011).

A few papers have focused solely on product platforms. Most of these include optimization models of supply chain and platform configurations. For example, Huang *et al.* (2007) studied product platform development and supply chain configuration through a game theory approach for a two-echelon supply chain and found that manufacturers experienced decreasing inventory costs, but tended to accept higher prices from the supplier in the presence of platforms. Zhang *et al.* (2010) also focused on configuration of platform products and supply chain, emphasizing supply chain performance and stressed that positive performance is related to good cooperative relationship between the supplier and manufacturer.

5.1.3 Multi-stage supply chains

The papers in this category emphasize the challenges of modularity when moving further upstream along the supply chain (e.g. to first- and second-tier suppliers) or optimize supply chains with multiple stages.

Doran (2003) studied the impact of modularization on the value-adding processes of key component suppliers, suggesting that value-transfer activity will impact not only the first-tier suppliers but also the second- and third-tier suppliers that form the key value-adding elements. In line with this, Doran *et al.* (2007) found that benefits and impacts, which are often associated with modularization, dissolve as it moves to second- and third-tier suppliers. Lau *et al.* (2010b) studied the relationship between product modularity and supply chain integration in Hong Kong and Pearl River Delta, and they found that loosely coordinated supply chains tend to be related to modular design, while tightly coordinated supply chains are related to integrated design. They highlighted the risk of technological knowledge leakage during product modularization. Pero *et al.* (2010) suggested that modularity does not necessarily reduce configuration complexity; for example, the modules that the first-tier suppliers supply to the OEM are not modular *per se*, and the first-tier suppliers have to manage a complex network of their own suppliers. Thus, modularity may decrease the configuration complexity from the viewpoint of the OEM, but not for the suppliers.

The earliest paper in this literature review – Lee and Sasser (1995) – used an analytical model in a practical case from HP to determine if the company should have universal or regional modules to serve different markets. The model considered several factors, such as markets, demand, lead times, plant locations and inventories. Their study showed that a universal

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power supply for the markets would lead to cost benefits, mostly coming from lower inventory, re-work and transshipment costs. Ernst and Kamrad (2000) studied supply chain structures in relation to modularization and postponement, finding that vertical integration (i.e. low degree of outsourcing and subcontracting component manufacturing) along the supply chains is not desirable; companies are replacing vertical integration with vertical coordination and developing long-term relations with outside suppliers. Hong and Hartley (2011) investigated buyer-supplier-supplier triads and found that modular designs reduce the need for information flow and processing between the two suppliers and the buyer.

5.2 Content analysis by product architecture type

5.2.1 Modular-integral spectrum

Research on the product architecture spectrum (modular to integral) has tended to polarize the supply chain design implications for modular and integral architectures. For example, Fine *et al.* (2005) proposed that modular–modular and integral–integral solutions are preferable to integral–modular or modular–integral solutions for product–supply chain design decisions, emphasizing the importance of aligning the architectural decisions across the supply chain. Yassine and Wissmann (2007) proposed that modularity will lead to increased product development time for the first round of products, wherefore companies that are interested in short time to market for the first round of products should select integral architectures. Caridi *et al.* (2012) included the project structure dimension and differentiated between high and low levels of modularity for products developed under a derivative process (i.e. incremental changes over time). They suggested that outsourcing and collaboration is advisable only for low modular products.

5.2.2 Modular design

Papers that have solely focused on the modular architecture *per se* have typically related this design approach to concepts such as mass customization and postponement as well as performance measures on cost, flexibility and complexity. For example, Mikkola and Skjøtt-Larsen (2004) discussed variety, customization and modular product architectures. They found that modules or sub-assemblies, which are differentiators of the final product, can be manufactured outside the main plant and located closer to the customer, hence, facilitating logistics postponement. El Hadj Khalaf *et al.* (2011) studied product families and supply chains with the conclusion that a standardization strategy, which allows for non-required extra functions to be included in the finished product, will reduce the total amount of modules in the supply chain and lead to reduced cost. Gualandris and Kalchschmidt (2013) found that product and process modularity allow firms to gain additional flexibility, which enables swift reactions to supplier failures. They argued that companies should identify their level of operational complexity and try to reduce it by implementing product and process modularity.

5.2.3 Platform

This small group of papers have mainly focused on the integrative aspects of supply chain and platform configuration, e.g. the papers by Huang *et al.* (2005), Huang *et al.* (2007), and Zhang *et al.* (2008, 2010). The scope of the configuration have been both within and beyond a particular manufacturer and have considered factors such as supplier selection, transportation mode, site selection and inventory policies in relation to platform products. For example, Huang *et al.* (2005) studied the optimal supply chain configuration for a product family with and without commonality. They found that product platform commonality significantly impacts the performance and the configuration of the supply chain; for example, platform commonality leads to an agile supply chain and inventory reduction for finished products. Zhang *et al.* (2010) studied the simultaneous configuration of platform products and their supply chains, concluding that manufacturing firms would prefer closer collaboration with its suppliers and that a high level of supply chain integration would enable the manufacturers to provide higher product variety.

5.3 Content analysis by research methodology

5.3.1 Case research

Papers taking a case methodological approach have focused on in-depth investigations into the interrelationship between product architecture and supply chain design. The case study papers average 3.5 cases per paper, ranging from one to six cases. As an example of a six-case study, Salvador *et al.* (2004) studied supply chain configuration for mass customization with two contingency variables: product customization and types of modularity. Based on a cross-case analysis, they found that product variants influence the supply chain configuration, such that high customization and many variants tended to require the final assembler to give up the task of producing components and instead control the overall product architecture. Single case studies have primarily tried to understand specific phenomena. Hofman *et al.* (2009) studied modular product architecture and supply chain networks using a single case study in the house-building industry, which is an industry that is rarely studied in-depth. Their findings suggested that various strategies need to be used depending on product variety, supplier knowledge and supplier investments. In addition, they stated that aligning the level of supplier integration with various modules is key to effective modularization. For example, modules that require supplier expertise knowledge are suited for full integration, while modules that are considered as commodity items can be bought through the open market with traditional procurement methods.

5.3.2 Conceptual modeling

All the conceptual papers fall into the category of general supply chains, and can fundamentally be divided into three categories:

1. alignment, i.e. designing the supply chain to match the products (Fine, 2000; Fisher, 1997; Fixson, 2005; Krikke *et al.*, 2004);
2. architectural-capability perspective, i.e. an evolutionary view on the relationship between design architecture and manufacturing capability (Fujimoto, 2007, 2012a, 2013); and
3. production-distribution networks, i.e. where and how products are produced, assembled and distributed (Feitzinger and Lee, 1997; Yassine and Wissmann, 2007).

These papers are, in general, authored by experienced and well-recognized researchers, that draw on insights from organizations with a global presence and strong customer visibility; e.g. Toyota (Fujimoto, 2007, 2012a, 2013); Hewlett-Packard (Feitzinger and Lee, 1997); and IBM, Intel and Chrysler (Fine, 2000). In particular, conceptual papers have been able to discuss the full architectural spectrum from modular to integral architectures in relation to general supply chain topics (Fine, 2000; Fixson, 2005; Yassine and Wissmann, 2007; Fujimoto, 2012a). The strength of conceptual modeling papers lies in its flexibility to incorporate several dimensions into one paper, drawing on inputs gathered from the long-term experience of the researcher, and that conceptual models can be powerful in explaining specific relationships that managers may find useful for decision-making.

5.3.3 Surveys

The survey papers have included a broad range of dimensions concerning the relationship between product architecture and supply chain design. While the coverage is broad and discussions have been included from both dyads and multi-stage supply chains, the data collection have focused solely on one actor in the supply chain, e.g. first-tier suppliers (Jacobs *et al.*, 2007; Hoetker *et al.*, 2007; Droge *et al.*, 2012) or the OEM/buying firm (Novak and Eppinger, 2001; Bush *et al.*, 2010; Hong and Hartley, 2011). We have been unable to find surveys that use respondents belonging to two or more consecutive stages in the same supply chain. Survey papers have collected data from different regions, e.g. Europe (Selldin and Olhager, 2007; Howard and Squire, 2007), Asia (Takeishi and Fujimoto, 2001; Lin, 2004) and North America (Jacobs *et al.*, 2007; Hoetker *et al.*, 2007). Although the respondents are located in a certain region, the papers have included a global perspective into the relationship between product architecture and supply chain design; for example, by having customers or suppliers located globally.

5.3.4 Mathematical modeling and simulation

The majority of the mathematical modeling and simulation papers have focused on buyer–supplier relationships with a particular focus on the integration and optimal configuration between product architecture and dyadic supply chains (Huang *et al.*, 2005; Zhang *et al.*, 2008; Ülkü and Schmidt, 2011). The typical objective function is cost minimization with a variety of cost elements typically related to production and transportation. Fine *et al.* (2005) used a goal programming approach to study the trade-off and potential conflicts that might arise between supply chain, product design and production planning. To manage the conflicting interests of these views, the objective function included product fidelity (the degree to which the design of the elements conforms to the tasks it is intended to perform), cost, lead-time, partnership and dependency. da Cunha *et al.* (2007) studied module-based mass customization using more classical supply chain cost elements such as assembly and transportation costs. They showed that optimal designs can save up to 25 per cent of the total cost. Chiu and Okudan (2011) studied when and how to incorporate supply chain decisions in product design with respect to process, transportation and inventory costs. They used a bicycle industry case and showed that modular product architecture with suitable supply chain design can reduce the inventory cost and lead time.

6. Thematic findings

We have identified five key themes in the literature on the relationship between product architecture and supply chain design. These themes are driven by the content analysis and drawn from an overall assessment and cross-comparison of the literature. Four themes are concerned with the use of external suppliers, which can play an important role in the development and production, particularly for modular products (Doran, 2003). The themes related to external suppliers are: outsourcing, supplier selection, supplier relationships and distance from focal firm. The fifth theme is alignment, i.e. that the supply chain design type matches the product design type. These themes are not mutually exclusive. A paper can address more than one theme. For example, alignment can be an issue in the other themes. However, we focus on the main perspective, issue or idea of each paper, wherefore a paper appears in only one of the five themes. Table III summarizes the themes and the associated primary literature sources.

6.1 Outsourcing

Outsourcing has gained interest for modular designs, as modular product architecture involves standard interfaces that help to decouple significant portions of product design and manufacturing. Nepal *et al.* (2012) noted that modular product designs tend to result in outsourcing and transfer of components to suppliers. Doran *et al.* (2007) argued that, with modular product design, value-added activities are shifted from a single organization to the overall modular supply chain, as the key modules are outsourced to technically competent module suppliers. Still, this can be restricted to less critical modules, while core modules are manufactured in-house (Lau *et al.*, 2010b). Ciravegna *et al.* (2013) stated that full service companies can develop a modular product and provide specific niche manufacturing. Novak and Eppinger (2001)

Table III Research themes on the interaction of product architecture and supply chain design, and the associated primary literature sources

Themes	Primary sources
Outsourcing	Novak and Eppinger (2001), Doran *et al.* (2007), Lau *et al.* (2010b), Ülkü and Schmidt (2011), Nepal *et al.* (2012), Ciravegna *et al.* (2013)
Supplier selection	Fisher (1997), Fine *et al.* (2005), Huang *et al.* (2007), Zhang *et al.* (2008), Chiu and Okudan (2011), Nepal *et al.* (2012)
Supplier relationships	Howard and Squire (2007), Zhang *et al.* (2010), Lau (2011), Ülkü and Schmidt (2011)
Distance from focal firm	Takeishi and Fujimoto (2001), Doran *et al.* (2007), Pero *et al.* (2010)
Alignment	Fisher (1997), Fine (2000), Salvador *et al.* (2004), Krikke *et al.* (2004), Fine *et al.* (2005), Howard and Squire (2007), Selldin and Olhager (2007), Fixson and Park (2008), Hofman *et al.* (2009), Lo and Power (2010), Ülkü and Schmidt (2011), Caridi *et al.* (2012)

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found that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate development of complex designs. They suggested that there are benefits to concentrating production of complex systems in-house and to outsourcing simpler systems, arguing that profit-maximizing firms should only operate according to these approaches. Ülkü and Schmidt (2011) concluded that outsourcing does not necessarily result in more modular architectures; it is the capability differences between firms and its suppliers that have an influential role in determining the product architecture.

6.2 Supplier selection

Fisher (1997) suggested alternative approaches to choosing suppliers for the two types of supply chains he identified: select primarily for cost and quality in efficient supply chains versus select primarily for speed, flexibility and quality in responsive supply chains. Many mathematical models include supplier selection as an ingredient in the optimization model, often together with the selection of module options (Huang *et al.*, 2007 and Zhang *et al.*, 2008). The supply network is a key element in the goal programming model by Fine *et al.* (2005), with five different supply options: catalog, in-house, supplier–partner, local supplier and international supplier. Chiu and Okudan (2011) presented an integrated methodology for supplier selection during the product design stage for product and supply chain design decisions. Their model evaluated the impact of the supplier selection on both internal (e.g. ease of assembly) and external (e.g. transportation time) enterprise performances. Nepal *et al.* (2012) proposed a three-step process:

1 selection of product architecture;
2 evaluation of potential suppliers; and
3 optimal configuration of supply chain.

They balance the need to select suppliers with high compatibility ratings, which can often be more expensive, versus the ability to outsource modules at lower costs in modular designs.

6.3 Supplier relationships

The nature of the relationship between the original equipment manufacturer and its supplier (adversarial or collaborative) plays a role in the choice of product architecture. Ülkü and Schmidt (2011) found that supplier relationship and product architectural design are interdependent, such that modular architectures are more likely when the parties have adversarial relationships, while long-term trust-based relationships facilitate more integral product architectures. Lau (2011, p. 180) found a need for long-term partnership for modular suppliers, as:

> [. . .] modules are usually developed for use in a series of products on a long-term basis, manufacturers are required to ensure that the suppliers are technically competent and tend to develop long-term partnerships with them.

Howard and Squire (2007) argued that a shift in responsibility from OEM to suppliers provides opportunities for joint investigations into new technologies and parallel development of product and process innovation, wherefore modularity is more likely to lead to collaboration under conditions of co-developmental partnership. This appears to contradict the view that increased product modularization will lead to an arm's-length, black box approach to buyer–supplier relationships, where the outsourcing of design and delivery of component sub-assemblies leads to increasing supplier independence (Howard and Squire, 2007). In a mathematical model incorporating three types of suppliers (non-interactive suppliers, non-cooperative supplier and cooperative supplier), Zhang *et al.* (2010) found that the manufacturer would prefer a cooperative relationship with all types of suppliers, which would lead to lower costs and higher product variety.

6.4 Distance from focal firm

The issue of the diminishing returns of product modularization with the distance to the modularization firm in the supply chain can be identified in two papers: Doran *et al.* (2007) and Pero *et al.* (2010). Distance is viewed in terms of the supply chain position, i.e. the number of stages from the focal firm. Doran *et al.* (2007, p. 10) found that:

> [. . .] the impact and the benefits associated with modularisation naturally dissipate as one moves towards 2nd and 3rd tiers of the supply chain. This said, one can also observe that those suppliers that might be regarded as distant from the modular epicentre are modularising to a lesser degree by examining value transfer activity and value creation activities that, in their own way, could be regarded as modular activity, albeit at a more localised level.

Pero *et al.* (2010, p. 9) found that:

> [. . .] modularity does not necessarily reduce configuration complexity. The automotive suppliers (companies A and B) produce modules for the original equipment manufacturer (OEM), but their products are not modular and they have to manage a complex network of suppliers. Modularity decreases configuration complexity from the point of view of the original equipment manufacturer (OEM) but not from the suppliers' viewpoint.

Furthermore, Takeishi and Fujimoto (2001) studied first-tier OEM suppliers and automakers in Japan, and found that the perception of product architecture was based on where in the dyad the specific actor was located. They found that component suppliers perceived the product architecture as integral, while the OEM regarded it as modularization. Thus, the benefits of modularization may be very local.

6.5 Alignment

Fisher (1997) highlighted the need to match the supply chain to the product. He observed that supply chain strategy (efficient vs responsive) should be defined according to the product type (functional vs innovative). He specifically mentioned modular design to postpone product differentiation for as long as possible in the responsive process. This model has been tested empirically. Selldin and Olhager (2007) provided some support to Fisher's model, showing that the alignment of the product with network design is significant for delivery speed, delivery dependability and cost performance. Lo and Power (2010) found that a hybrid strategy (pursuing both efficiency and responsiveness) is used by most organizations irrespective of the nature of the primary product they supply. Both studies report that some companies mix characteristics of both supply chain strategies, pointing to the problematic association between product nature and supply chain strategy. Hofman *et al.* (2009) found that matching the degree of product variety to the supply chain structure leads to enhanced performance. The alignment between product modules and supplier relationships were found to be

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contingent on four drivers: the degree of variety in customer demand, the extent of required supplier investment, the level of dependence on supplier knowledge and the intentions of both the supplier and the buyer in a relationship.

The concept of modularity can be used for both product and supply chain design. Fine (2000) claimed that the degree of modularity in the final output product has a one-to-one correspondence with the degree of modularity in transformation processes and supply chains. A modular supply chain is regarded as suitable for a modular product design, and an integral supply chain is preferable for an integral product design (Fine *et al.*, 2005). Fixson and Park (2008) found that many products are becoming more modular over time, and that this development is often associated with a change in industry structure toward higher degrees of specialization. Thus, there may be a gradual movement toward a combination of modular products and modular supply chains. However, Caridi *et al.* (2012), Howard and Squire (2007) and Ülku and Schmidt (2011) indicate that other relationships between product architecture and supply chain design are possible. Salvador *et al.* (2004) discussed alignment within the type of modularity: "soft" component-swapping modularity and "hard" combinatorial modularity configurations, and that this has implications for supply, manufacturing and distribution. Finally, Krikke *et al.* (2004) extended the Fisher framework to closed-loop supply chains in which the design depends on the type of return flow.

7. Research agenda

Based on the content analysis of the extant literature on the design of global production and distribution networks, we can identify some opportunities for further research. In particular, we propose the following research agenda, which we hope can stimulate further research.

7.1 Case studies

There is a lack of case studies describing how companies actually integrate and align product architecture with the supply chain and other functions (Khan *et al.*, 2012). Even though 14 case studies have been identified in this research, we feel that more case studies can offer more details and insights into these relationships. The existent case studies are concerned with the impact of the product architecture on various supply chain decisions, aiming at finding an optimal supply chain for the product. It would be interesting to learn more about the reverse direction, i.e. how global factors (such as local content requirements; local environmental regulations; and market types, location and sizes) can influence the product architecture decision. In addition, it would be most interesting to learn about successful integral product designs and its associated global supply chains.

7.2 Integral design

No single paper has focused on the integral design and its relationship with the supply chain. To some extent, this issue is included in the papers that discuss the product architecture spectrum from integral to modular designs. However, there is a bias in this literature, in that modular designs are typically favorable over integral designs. Because modular products are easier to imitate than integral products (Ethiraj *et al.*, 2008), many companies are now turning to integral designs (Fujimoto, 2012b). We need to know more about the link between integral product designs and how to design competitive supply chains for such products. Consequently, research that can provide examples and structural approaches for the interaction between integral product designs and global supply chains is warranted.

7.3 Mixed product architectures

No single paper focuses on mixed product architecture. Most typically, the available research focuses on modular designs, even though integral design is acknowledged as an alternative which may even be used for some parts of the final product. In practice, extreme modular designs or extreme integral designs are usually not found; instead, many real-life examples are a mix of integral and modular designs. This means that companies need to take this into account and potentially design different supply chains for the items that are related to the modular part of the product versus the items that are related to the integral part of the product. This may well be an important contingency leading to segmentation of supply chains. Research on the design and impact of mixed product architectures on global supply chains is needed.

7.4 Multi-stage supply chains

There are only nine articles on product architectures in multi-stage supply chains in the available literature. Papers that can capture this added complexity and still convey insightful messages are commendable. We could not find any survey that collected data from two or more organizations in the supply chain. Combined interviews and surveys to multiple respondents along the supply chain would be of the utmost interest. Multiple respondents at each site may include product line managers/product development managers, as well as supply chain managers. A particular issue to investigate is the possibility of diminishing returns of the modularization effects with the distance to the modular design firm. Is there possibly a (positive or negative) bullwhip-type effect related to the level of product modularity?

7.5 Risk analysis and management

In the current literature, there is very little information on risks. For example, there is a lack of investigation on how product designs (e.g. modular) can help companies in mitigating supply chain risks (Khan *et al.*, 2012). We have identified four types of risks in this research:

1. inventory risks, to be alleviated by risk pooling, i.e. sharing inventory through commonality (Khan *et al.*, 2012);
2. copy risk, i.e. modular products are easier to imitate than integral products (Ethiraj *et al.*, 2008);
3. information risk, i.e. manufacturers worry about the risk of knowledge being leaked or imitated across the supply chain (Lau, 2011); and
4. supplier failure risks, particularly in industries, and periods with substantial entry and exit of suppliers (Hoetker *et al.*, 2007).

Thus, a broader framework for risk analysis and management with relevance for product architectures and supply chain design is warranted.

7.6 Supply chain impact on product architecture

While there is research on the impact of product architecture on supply chain design, there is no research that explicitly studies the reverse. Having an existing supply chain may lead to constraints in the product architecture, but taking a wider view on how a supply chain could be set up and how the corresponding product might be designed would provide interesting research opportunities. Research on the impact of a particular supply chain network on the choice of product architecture will complement research and findings concerned with the impact of product architecture on the locations and roles of production and logistics facilities. From a practice point of view, such research could provide interesting insights when designing new product generations and their corresponding supply chains.

8. Concluding remarks

In this paper, we reviewed the literature on the relationship between product architecture and supply chain design. A limitation of this study is that our search strategy may have missed some references that are related to the area. However, as a counter-measure, we used back-tracking and forward-tracking to identify additional relevant papers. We categorized the articles in three dimensions: product architecture type, supply chain type and research methodologies. We identified five key themes: outsourcing, supplier selection, supplier relationships, the distance from the focal firm and alignment. Four themes are related to the use of external suppliers, which can play an important role in the development and production of modular products. An integral product design, on the other hand, can lead to more in-house activities in terms of product development and production. However, no study is in complete agreement on this issue (Caridi *et al.*, 2012; Ernst and Kamrad, 2000; Novak and Eppinger, 2001; and Ülkü and Schmidt, 2011. Thus, more research is needed to support managers in making decisions on integrated product and supply chain design. We identified six areas for further research: case studies, integral designs, mixed product architectures, multi-stage supply chains, risk and the impact of supply chain design on the product architecture.

Even though a literature review typically aims at deriving a research agenda, some implications for managers can be identified. First, the literature supports the perception that the choices of product architecture and supply chain design are strongly interrelated, wherefore an integrated and concurrent design of products and supply chains is advocated. Second, external suppliers can play an important role, but careful consideration concerning outsourcing, supplier selection and supplier relationships is needed. However, more research is needed to obtain fuller understanding of the mutual impacts of product architecture and supply chain design, and to develop decision support tools for managers on how products should be designed and produced and which suppliers to use for which parts of the products.

The overall view is that there is a growing stream of research on the interaction of product architecture and supply chain design, and we hope that this review can be a useful and inspirational source for further research on this interesting and important topic.

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Appendix

Table A1 Previous literature reviews on supply chain design or product architecture

Source	Topic/perspective
Supply chain design:	
Thomas and Griffin (1996)	Coordination and planning aspects between two or more stages in the supply chain
Cohen and Mallik (1997)	Management of the intra-firm global supply chains
Vidal and Goetschalckx (1997)	Strategic design of global supply chains with emphasis on mixed integer programming models
Pontrandolfo and Okogbaa (1999)	Coordination aspects for the logistics and manufacturing networks
Sarmiento and Nagi (1999)	Integrated production – distribution models considering the transportation system
Goetschalckx *et al.* (2002)	Integrated strategic global supply chain networks with tactical production-distribution allocation and transfer prices
Bilgen and Ozkarahan (2004)	Strategic, tactical and operational production – distribution models
Schmidt and Wilhelm (2000)	Strategic, tactical and operational logistics network models
Meixell and Gargeya (2005)	Decision support models for design of global supply chains, focusing on the logistics aspects
Melo *et al.* (2009)	Facility location in the supply chain network
Product architecture and design:	
Gershenson *et al.* (2003)	Definitions and benefits of modular product design
Simpson (2004)	Product platform design and mass customization
Jose and Tollenaere (2005)	Modular and platform methods for product family design
Jiao *et al.* (2007)	Platform-based product development and product family design
Fixson (2007)	Modularity and commonality in the product, process and organizational context
Doran and Hill (2009)	Tools, techniques and concepts related to modular production within manufacturing operations
Campagnolo and Camuffo (2010)	Modularity in the context of product, production and organizations
Ravasi and Stigliani (2012)	Product design in the broader scope of management studies (e.g. marketing, innovation and operations)
Dekkers *et al.* (2013)	The interface between product design and engineering

About the authors

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