Modular Product Architecture to Manage Supply Chain Complexity

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***Abstract*—The aim of this article is to demonstrate and to eliminate or to reduce the complexities associated supply chain management. These complexities are aroused due to the high level of interdependencies between component interfaces and supply chain participants. A case example is presented to define the importance of product architecture with the help of design structure matrix (DSM) tool to reduce product development complexity. To address such complexity this work focuses on the product architecture and supply chain design. This research addresses the clear visibility how modular product design architecture contributes to reduce supply chain complexity. The relationship between product architecture and supply chain complexities is defined along with identifying and categorizing various drivers responsible for supply chain complexities.**

Keywords*—Product architecture, design structure matrix, modularity, complexity, component interfaces, supply chain*

1. Introduction

The objective to concentrate on product architecture is to ease of manufacturing and assembly processes [1]. Moreover, the functional characteristics of product depends on the product architecture. It is therefore, essential to optimize the design of product architecture [2]. Various things depend on product architecture such as production strategy weather it is integral or modular, number of components, make or buy decision, selection of suppliers or vendors, complexity in the supply and delivery process, product life cycle, repair and maintainability, shelf life, product recycling and retirement, etc. All such factors are considered as the intrinsic features to develop a quality and long lasting product.

One of the major concerns in today's product design and development domain is to consider modular design approaches over traditional integral approach. In order to adopt modular design approach, as much as possible, designers need to focus on the design of product architecture in such a way that modular product can be developed within shorter lead-time with required features and functionalities. In order to develop modular product, designers need to identify the required number of modulus to develop the specific product. However, often it is not easy to identify the modules. There are available methods and tools, through which modules can be identified such as heuristic method [3], modularity matrix [4], axiomatic design [5], design structure matrix (DSM) [17] tool, etc.

This research focused on product architecture, which is the key to manage complexity in any product. This architecture needs to be carefully designed by the designers to avoid or minimize product development complexity as well as supply chain complexity. In this avenue, the research identifies several complexity drivers of supply chain and their impact on modular architecture.

The rest of the paper is organized as follows: Section 2 express the existing literature in the field of product modularity architecture and supply chain complexity, Section 3 outlines the research methodology, while Section 4 briefs an overview of DSM tool. In Section 5, the complexity is defined with respect to modular supply chain perspectives with associated drivers. The relationship between product architecture and supply chain complexity is introduced in Section 6. A case example is highlighted in Section 7 to evaluate the supply chain complexity within product architecture. The paper is concluded in Section 8.

2. Theoretical framework

Supply chain is a system of individuals, organizations and the flow of resources, services, activities and information between them [6]. This implies that it is an integration or management of all the processes across the supply chain network. The network of supply chain is an essential part to many successful industries around the globe. Due

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to the globalization of business domain, the importance of supply chain is getting profound more than ever. It is therefore critical for organization to manage their supply chain network as smoothly as possible. However, often, it is not an easy task to manage supply chain network according to the needs [7]. Efficient and effective management of the network poses many hurdles and challenges [8]. Today's supply chain exhibit a large and complex interaction with their suppliers, customers and other firms thereby making the chain complex to manage.

Supply chain complexity can be defined as the complexity demonstrated by the products, processes and relationships that make up a chain. According to Ref. [9] "complexity has been the topic of several manufacturing, organizational, and information technology studies creating a variety of definitions and applications depending on the perspective and/or theories". Ref. [10] defined complexity in supply chain as the risks or the difficulties that arises within various entities of supply chain during conceptualization, production and distribution of product. On the other hand, Ref. [11] relate supply chain complexity with the product design/ architecture. Moreover, Ref. [12] found that the presence of complexity driver increases the frequency of supply chain disruptions, as well as, the drivers interact and amplify each other's effects in a synergistic manner.

There are very limited existing researches that studies the interaction between product architecture and supply chain complexity. Most of the previous researches are focused on product architecture and supply chain design. From literature, it is notice that proper product design contributes to minimize supply chain complexity [11, 13]. It is therefore critical to focus on product design complexity before focusing on supply related complexity. For instance, modular product design reduces supply chain complexity substantially [14, 15]. An efficient product design depends on its architecture, which need to be focused by the product designers. The design of efficient product architecture with the perspective to reduce complexity in supply and logistics chain could provide interesting insights when designing new product generations and their corresponding supply chains. From a practice point of view, this research gap is explored within the scope of this research.

3. Research methodology

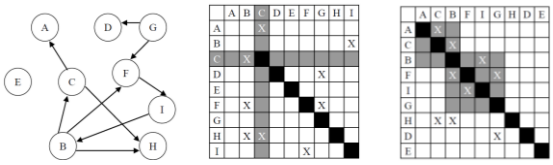
To perform this research, an exploratory case study approach was taken with the objective to investigate information flows or component interdependencies within the product architecture to reduce complexity. This research started by reviewing the relevant literature in information processing, which is related to product modularity to reduce complexity in product development phase. Based on the literature review, this study involves components interdependencies and their consequences to form modular architecture and the clustering effects on product architecture.

The required data to know the component interdependencies with dependency level were collected from the case company by interviewing, from weekly\bi-weekly meeting with managers, designers, engineers, from active participation in the company's daily assembly lines and from the company's standard database. In addition to collect the valuable data, the generic objective of the meetings was to reveal various complexities and weaknesses of the case company. In this study, two tools namely PSM32 and DSM were used to formulate modules and analyse the outcomes.

4. Design structure matrix: a tool used to identify modules within a product architecture

In this paper, the DSM tool is used which is widely used in organizations for its simplicity and ease of identifying modules. This tool is also extensively used to minimize design complexity related to product development. This tool is developed by Ref. [39], which is a kind of square matrix, where the cells on the upper left to lower right diagonal indicate the components of a product or elements of a system and off-diagonal cells indicate the interdependencies between components or elements. The DSM can be defined as a design methodology to support product designers to identify modules within product architecture [16]. The formation of modules helps to design and measure modular design strategy. Not only in the area of product design and development, modular design principle is also extensively used in other areas, such as organizational design, human resource management, supply chain management, service industries, process design, etc.

In order to identify modules within product architecture all the components within the product are populated in DSM and their interactions or interdependencies are marked on it. Based on their interdependencies necessary modules are formed. The modules are formed following partitioning algorithm, which helps module formation considering the closeness of interfaces of the components with each other [20].



(a) (b) (c)

Figure 1. (a) Display of components interdependencies through spaghetti diagram, (b) Representations of components interdependencies through the DSM tool, (b) Partitioned components interdependencies through the DSM tool [26]

In general, the DSM is a square matrix, where each rows and columns are assigned with the components names of a product and the cells of the matrix are marked by the dependency. The DSM concept is displayed in Figure 1 (a, b, c) as an example. Figure 1(a) visualizes the simple interdependencies of the components, while Figure 1(b) displays the same interdependencies over a matrix format. For instance, from Figure 1(a) it is seen that component 'C' depends on component 'B' and components 'A' and 'H' depends on component 'C'. These interdependencies are displayed in Figure 1(b). The partitioned or clustered DSM is also displayed in Figure 1(c), where two overlapping modules are identified following the clustering algorithm.

5. Modular supply chain management: complexity and associated drivers

Managing supply chain successfully is considered as an important parameter for business success. It is therefore, a prime concern for manufacturing companies to efficiently manage their supply chain. However, it is often not an easy task to manage supply chain but faces several challenges. These challenges are caused initially by overall design strategy and several known and unknown factors, commonly known as drivers within a company.

With respect to modular design strategy, supply chain behaves comfortably over integral design strategy [19]. In modular strategy, it is easier to manage each module separately through the entire supply chain [20]. If the module cannot be manufactured or assembly internally, it can be ordered to the corresponding supplier based on its capacity. The specific module also can be ordered within supply chains based on competitive suppliers' survey [21]. As the modules are separated which are assembled finally in the core factory, it is also comfortable not only to order separately but easier to transport and maintain the inventory level.

On the other hand, if the design strategy is taken as integral principle it might then create extra complexity towards the supply chain to manage it properly. This is due to the nature of components, which are highly dependent on each other and cannot easily separable. This integral design issue also brings extra pressure in terms of repair and maintainability [22].

In addition to design strategy, there are several factors, commonly known as drivers, which influence supply chain complexity. Based on such characteristics, supply chain complexity drivers can be divided as internal complexity drivers, external complexity drivers and interfacial complexity drivers. Internal complexity drivers are defined as the factors effect on supply chain internally to the organization, while, external drivers are associated outside the organizational boundary. The interfacial complexity drivers are the drivers, which are interfaced between suppliers and customers and exist between internal and external complexities. All major drivers for internal, external and interfacial complexities associated with supply chain complexities are presented in Table 1. From Table 1, it is seen that internal complexities are mainly on product development strategies, whereas, external complexities are associated with facilitates the product development processes in order to be profitable, and interfacial complexities are related to mostly on suppliers sides.

Table 1. Major drivers of supply chain complexity

Type of supply chain complexity	Major drivers for supply chain complexity
Internal complexity	• Number of product variants [23, 24]
	• Operational processes [25]
	• Information exchange [26]
	• Planning and scheduling [12, 27]
	• Inventory management [27, 28]
	• Marketing and sales promotion [29]
External Complexity	• Transportation and logistics [28]
	• Tracking and tracing of logistics chain [30]
	• Demand fluctuation [27]
	• Product retirement and recycling [23]
	• Political factors [31]
	• Geographical location [28]
Interfacial Complexity	• Number of suppliers [7]
	• Suppliers location [32]
	• Incompatible supply chain network [33]
	• Collaborative supply chain [34]
	• Competitive supply chain [35]

6. Relationship between product architecture and supply chain complexity

As defined above, product architecture deals with the functionality of a product. The design of the product architecture is considered as an important parameter to create product variants. The development of product variant needs increased number of components or parts, which create complexity in the production line, especially to the supply chain networks [33]. Often it is required to a manufacturing firm to buy or import components from its suppliers to create product variants. The management of such supply chain need to be transparent in order to ensure readily available component [35].

During the design of a product architecture, it is necessary to keep in mind about its total supply network from where each of the necessary components might supply. Whether the components are manufactured internally within a factory or collected from the supplier both cases product architecture influence substantially. In case of internal production, the components need to be assorted and stored efficiently to get them on demand. On the other hand, outsourced components are needed to be transported just in time in order to avoid production delay [36].

It is often difficult to track the location of transported components or parts within the supply chain. This tracking process helps to reduce the complexity associated to delayed arrival of the ordered components to the factory premises. It is necessary to introduce risk pooling within the supply chain in order to ensure late customization or implement postponement strategy. To maintain optimal service level and maintaining delivery schedule, it is necessary to make contractual agreement with the suppliers to ensure on time component supply.

In addition to supply chain design, the product architecture also influences over the engineering analysis of the individual product versus product family. During component selection process, each component can be ordered to the corresponding supplier depending on its interface standardization with other related component [37]. This way it might be easier to select the component supplier who can supply majority of the components, which are interfaced, or highly dependent with each other. This principle also helpful to the strategy of component standardization that supports function-component allocation style within the supply chain.

7. Case example to evaluate supply chain complexity within product architecture

The study was started with collecting data related to architectural design of the studied engine of a case company engaged in energy business. The required data were collected by asking questions to the product designers, supervisors, project managers, supply chain managers and workers. The interviewees were all experienced managers and decision-makers at different levels of responsibility within the organization. Several meetings/workshops were arranged and company's design database were used to get the data too.

During the case study, the author had access to the documents related to the engine project (e.g. product documentation, process descriptions). The collected data were related to the number of components, number of components interfaces, components interdependencies with each other, and strength or level of dependencies, number of suppliers and their locations.

The data as collected from the case company were then analyzed using design structure matrix (DSM) tool to study the engine's product architecture and to identify modules. The engine consisted of 228 components, which were populated over the DSM tool, and their interdependencies are marked with the level of dependency strength such as high, medium, and low. Figure 2 displays some of the components interdependencies out of total 228 components of the engine. All the red marks are displays as higher dependency and marked with number '1', while yellow and green marks with number '2' and '3' are displayed as medium and lower dependencies respectively.

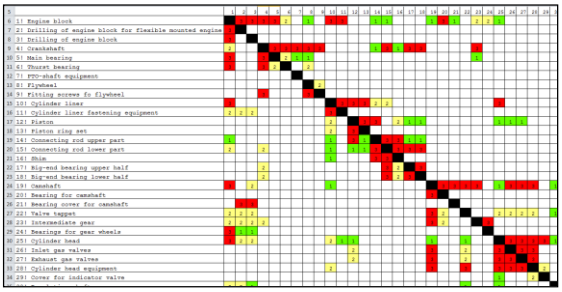


Figure 2. Close look of some of the components interdependencies with colours and numbers within the case company's product

The dependencies of the components are partitioned following the clustering algorithm within the DSM tool and the resultant modules or clusters are displayed in Figure 3. From Figure 3, it is seen that the product architecture of the case company's product is highly integrated and complex in nature. This complexity is aroused due to the high dependence among the components. It is noticed from Figure 3 that three large modules are developed encompassing one by other, which clearly indicates complexity in the product architecture. This complexity can be reduced by redefining the existing engine architecture in order to redesign the architecture to develop manageable number of modules with reasonable number of components in them.

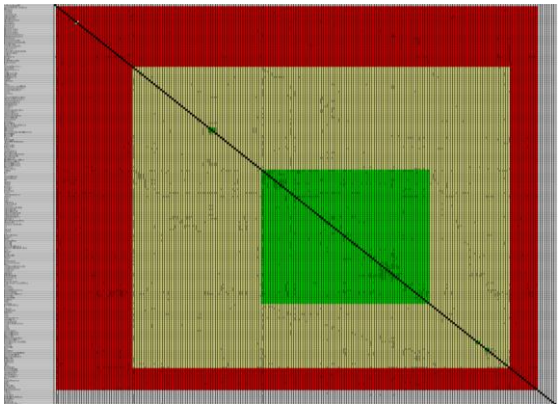


Figure 3. Display of components interdependencies within the case company's product

These complex modules create extra bottlenecks to the logistics and supply chain areas. Due to the integrated and bigger size modules, it is often difficult to the suppliers to supply such complicated modules to the original equipment manufacturers (OEMs). On the other hand, if the modules are smaller with limited number of components it creates easy job for the suppliers to design and develop such modules and deliver to the OEMs. These smaller size modules also facilitates to deliver through transportation and logistics chain. It is therefore, highly recommended to resist the product architecture and develop the modules with relatively smaller sizes and to avoid logistics and supply chain complexity with respect to design and delivery point of view.

8. Conclusions

Today's manufacturing companies are operating in competitive market environments, where customer demands are becoming more heterogeneous and product life cycles are steadily shortening. In order to tackle higher levels of demand variety and less time to market, companies need to take right decisions early in the product development process on the success of a product. In general, it is important to take early design decisions on all steps in the product value chain. Out of many decisions, one of the key issue is to take a comprehensive decision on product architecture. The product architecture can be used as a guideline to focus on design decisions critical for the product and company under consideration [38]. It integrates product development, operations management and supply chain management.

As discussed within the scope of this research, the product architecture is intrinsically related to the complexity of a product. By defining the product architecture efficiently, it is substantially possible to reduce product development complexity. The complexity associated with product development processes are of various types and formats, which can be in the form of design strategy, assemble ability, maintainability, availability, etc. [38]. All such complexity issues are directly related to number of components, number of interfaces, dependency of components with each other, etc. If the designers are managed to design the product architecture of a specific product efficiently, it will contribute substantially to reduce complexity related to manufacturing, assembly and managing supply chain.

The research objective is met by identifying supply chain complexity with respect to product architecture. Impact of product architecture on supply chain design is discussed within the scope of this research. It is studied that designing appropriate product architecture can reduce supply chain complexity by proper management of transportation, inventory level, order and delivery, etc. The fundamental drivers for supply chain complexity are also identified within the objective to define and manage them efficiently to reduce the supply chain complexity. The drivers are categorized as internal, external and interfacial accordingly. Any company to measure its supply chain complexity level can use the identified drivers and required steps can be taken to eliminate or reduce such complexity issue [38].

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