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Modular product architecture to manage product development complexity

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Abstract: Shorter product life cycles, together with heterogeneous market demands, are forcing manufacturing companies to eliminate or reduce complexities in product development and supply chain. These complexities arise due to high level of interdependencies between component interfaces and supply chain participants. To address such complexities, companies need to focus on their product architecture and supply chain design. In this research, the impact of product architecture on developing modular products is highlighted. This modular principle is elaborated with the objective to reduce product development complexities. A case example is presented to define the importance of product architecture with the help of a design structure matrix (DSM) tool to reduce product development complexity. In addition, various drivers responsible for supply chain complexities are identified and categorized, and the relationship between product architecture and supply chain complexities are defined within the scope of this research.

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

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1. Introduction

In recent years, the competition has intensified for many companies, especially small and medium enterprises (SMEs), through increased variation of customers' demands and a shorter product life cycle. In order to attend such demand heterogeneity, many firms are moving towards product customization, where individual customers' orders can be satisfied economically (McDermott et al., 2013). This customization strategy could be successful by considering manufacturing concerns during product design and overlapping traditional sequential design processes with concurrent engineering (Fixon, 2005; Marion et al., 2015; Hasan et al., 2016). In order to implement such a strategy, manufacturing companies need to concentrate more on their product architecture, through which products can be developed within a shorter lead time and with better quality. The product architecture can be defined as the identified elements of a product and their relations (Kristianto and Helo, 2014; Brunoe et al., 2017; Erikstad, 2019).

Concentrating on modular product architecture helps to ease both manufacturing and assembly processes (Boothroyd et al., 2002; Terwiesch et al. 2002: Shamsuzzoha et al., 2009; Cheng et al., 2018). Modular product architecture has a tremendous impact upon customer satisfaction and market acceptance of products manufactured by firms. Proper design of product architecture contributes to cost savings, improves manufacturability, and helps with other production-driven concerns as well (Ma et al., 2019). Modular product architecture is generally considered the mapping of components within a complete product, displaying the interdependencies of components within the product. From such mapping, designers can improve the design bottlenecks, if there are any. Product architecture has five areas of managerial importance, namely product change, product variety, component standardization, product performance, and product development management (Ulrich, 1995).

In modular product architecture, the modules, which are clusters of various components in a product, can be used successfully to develop variety (Pashaei and Olhager, 2019). Successfully developed modules can also be easily updated on regular time cycles, some can be easily removed if they fail or are retired, and some can be easily swapped to achieve extended benefits (Dahmus et al., 2001). In addition, standard modules are easily used in various different products that serve identifiable functions. Modularization supports developing a product family that is used to develop multiple products. Due to its ability to offer extended product variety, firms are moving towards a modular product design and development phenomenon and away from traditional integral product architecture. It is important for product designers to focus on the product architecture in order to develop modular product as much as possible (Shamsuzzoha, 2018).

There are several available methods and tools to identify and develop modules within a product, such as the heuristic method (Stone et al., 2000), modularity matrix (Dahmus et al., 2001), axiomatic design (Tseng and Jiao, 1997), design structure matrix (DSM) tool (Steward, 1981), etc. This research identifies modules using a DSM tool. The objective of this demonstration is to visualize the importance of product architecture to eliminate or reduce the product development complexities. In addition, this study also identifies the key performance indicators (KPIs) and associated drivers that can be used to measure product complexity level in general. The objectives of this research study are therefore summarized as follows:

(1) To investigate modular product architecture with respect to managing product development complexity.
(2) To identify KPIs and associated drivers that can be used to measure product development complexity.

The rest of the paper is organized as follows. Section 2 discusses the existing literature in the field of product architecture and the related complexities, while Section 3 outlines the research methodology in general. Section 4 provides an overview of product architecture and its effects on product modularity and design complexity. Section 5 defines how to reduce complexity in products through a modular design approach. In Section 6, the complexity is defined with respect to modular product development perspectives with associated drivers. The KPIs to describe the product architecture are outlined in Section 7. A case example is highlighted in Section 8 to evaluate the complexity within the product architecture. Overall, managerial implications are illustrated in Section 9, while this research is concluded with future research directions in Section 10.

2. Theoretical framework

2.1 Product development complexity

Various strategies exist to control complexity in the design and manufacturing of product. One of the most significant strategies that has come into prominence is the concept of modular product architecture (Baldwin and Clark, 2006). Such architecture provides an efficient way to address the issues of complexity that arises in the industry while manufacturing a product (Weiser et al., 2016). Product modularity is defined as "the practice of using standardized modules so that they can be easily reassembled/rearranged into different functional forms, or shared across different product lines" (Tu et al., 2004). Modular product architecture facilitates the standardization of product components while simultaneously making it possible to produce a large variety of products (Ishii, 1998). Over the last decade, modular product design philosophy has received lots of attention, evident form the publication of burgeoning literature in this area (Cheung and Leung, 2000; Agard and Penz, 2009; Jung and Simpson, 2017). The reason for this attention is due to its inherent ability to reduce complexity in terms of design efforts (Martin and Ishii, 2002; Eppinger, 1991; Zhang and Thomson, 2015; Mondragon and Mondragon, 2018).

Product development complexity represents a major issue in the area of product design. Therefore, the problems and consequences resulting from complexity must be dealt with in an appropriate manner. Complexity in product design is affected by factors such as performance choices, technology, and product architecture (Novak and Eppinger, 2001). According to Malmiry et al. (2016), complexity in product design can be illustrated from different points of view. Weber (2005) views design complexity from a product development, measurement, and formalization viewpoint. On the other hand, Suh (2005) defined complexity in terms of understanding the behavior of the system and achieving the product's functional requirements. Elmeraghy and Urbanic (2003) defined complexity as an obstacle to effective product development, and they studied product complexity as it is related to the design and specifications specific to each component of a product.

Zhang and Thompson (2015) introduced an agent-based model to study the impact of complexity during product design. Through a simulation analysis, they concluded that complex and innovative products require coordination that is more effective. In product design, a specific focus is on the product architecture, which describes the dependency structure within components of a product (Lindemann et al., 2009; Hu et al., 2008). On particularly good review on complexity in the design and manufacturing of products can be found in Elmeraghy et al. (2012). The product design and development complexity depends mostly on the nature of the product architecture (Fixon, 2005). From a product design perspective, product designers' intrinsic analysis of the architecture may reduce the product development complexity by improving manufacturability, ease of assembly, inventory management, supply chain management, repair and maintainability, etc. (Baldwin and Clark, 2006; Zhang et al., 2019).

2.2 Complexity related to product modularity

Apart from allowing manufacturers to cope with rapidly changing customer needs, product modularity also supports coping with increasing technical complexity in production processes, thereby allowing manufacturers to achieve high flexibility (Xiaosong et al., 2011; Salvador, 2007). Fredriksson (2006) analyzed the interrelationship between modularity and production processes in an assembly line. There is a high coordination between the unit production module and the unit assembling the final product. This implies that an increase in the level of modularity in the product design will reduce the complexity that arises within the supply chain partner during the manufacturing process. From a product design point of view, three important elements of complexity are the number of product components to produce, management issues related to the extent of interactions between these components, and the degree of product novelty in the product architecture (Novak and Eppinger, 2001).

There are several factors on which companies need to focus in order to reduce the complexity level in their product portfolio. Figure 1 displays several important factors that affect product complexity. From Figure 1, it can be seen that product complexity mainly depends on the development strategy, such as modularity, component interfaces, component standardization, and number of components. All such factors are directly related to product architecture. From the presented exploratory case example, it is evident that component interfaces or interdependencies are directly influenced over the modular or integral product development strategy. In cases of integral architecture, it is difficult to design or redesign any component or its interfaces, as it will significantly affect other related components. Whereas, in modular design approach, modules can be separated and/or designed or redesigned depending on the overall design requirements.

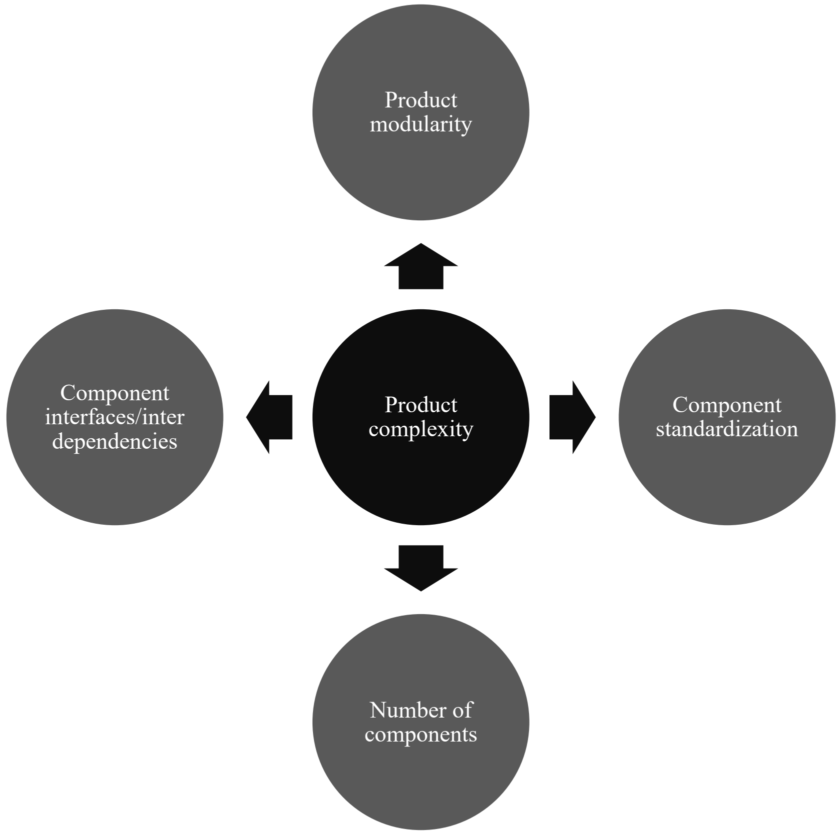

Figure 1. Display of various domains' effect on product complexity

From Figure 1, it can also be observed that more standard components contribute to fewer interfaces, which directly helps to reduce product complexity. Standard components also can easily be used across a family of products. In addition, the number of components contributes to complexity as well, as it is often difficult to correctly design their interfaces. A higher number of components results in enhanced complexity and vice versa. All such factors are used as KPIs to measure the product complexity level.

3. Research methodology

In order to conduct this research study, an extensive literature survey was conducted to identify the relationship between modular product architecture and product development complexity. In addition, this literature review was also used to identify the potential KPIs and drivers associated with product development complexity. An exploratory case study was conducted and presented within the scope of this research with the objective of demonstrating the concept of product modularity and how modules are identified within a product architecture. Through this case example, it was possible to investigate the necessary information flows or component interdependencies within the product architecture. This information exchange is very important to managing product development complexity.

The case study was conducted within a prominent global leader in the energy sector. One of the company's products was selected to study product modularity and associated complexity. This study was focused on looking for the components' interdependencies and their consequences within the selected product. Such components' interdependencies were analyzed using the DSM tool to identify the potential modules within the product. The DSM tool (www.dsmweb.org), which was developed by Steward (1981), is considered one of the best tools to identify modules within products, systems, or organizations. This tool is easy to use and offers excellent service to identify modules.

The DSM tool was used after collecting essential data from the case company by interviewing product designers, product managers, engineers, and operators who actively participate in the company's daily assembly lines. In addition, necessary product development-related data are also collected from the company's standard database. The generic objective of the interviews was also to reveal various complexities and weaknesses of the case company's product development processes.

At the end of the study, necessary recommendations were provided to the company to improve its product architecture and to cope with the existing complexities or bottlenecks. This exploratory case study research was adopted with the objective of validating the research scopes and to demonstrate how these could be validated for the mutual benefit for the case company. The research objectives were fulfilled and justified by investigating the case company's product lines; namely, information perspectives, modular design strategies, and clustering between the company's solutions with the current component architecture. Due to the issue of confidentiality, mostly sample data sets were used for this research study. In this study, two software tools, namely PSM32 and DSM, were used to formulate modules and analyze the outcomes.

4. Product architecture: effects on product modularity and design complexity

The product architecture encompasses the relevant information of a product, such as how many components the product consists of, how these components are interfaced or interdependent with each other, how they are built and disassembled, etc. It serves as the physical building blocks of a product in terms of what they do and what their interfaces are to the rest of the product (Ulrich, 2003). The product architecture therefore can be used as a comprehensive description of the fundamental structure of a product. A proper or error-free product architecture helps to reduce design complexity and enhance product customization.

Based on the product architecture, various strategic and operational decisions were taken, such as process and supply chain design, complexity of components, component commonality, product modularity, etc. The structure of the product architecture affects the task structure of the product development organization and the task structure, which in turn contributes to the organization performance (Lampon et al., 2017). This task structure determines the interaction and communication pattern between design teams, which directly effects the design complexity within an organization.

The adoption of a modular design strategy allows the company to regroup components into fewer modules, which is considered a way out to shorten product development time and support reduction of product complexity. In addition to modular product architecture, standard modules can be reused across product families, which thereby contribute to reduction of complexity. In a similar manner, from the modular architecture, a product designer can choose to overlap the development activities between the components or promote the reduction of process iterations. For instance, reducing the degree of component interactions has been found to positively affect the product development lead time, which also supports the reduction of the complexity level (Loch et al., 2003; Fixon, 2005).

The product architecture influences relevant decisions within organizations, including the production schedule, team organization, and the required maintenance planning. Such decisions affect the product characteristics through design decisions in the product development process. On a strategical level, such decisions vary depending on the product's characteristics. The decisions on product characteristics are related to the number of components, degree of component interdependencies, complexity of the individual components, etc.

In general, higher component or part complexity influences the need for complex manufacturing processes that result in higher production costs in comparison to simpler components, which require a simpler processes (Banker et al., 1990). This complexity affects the design for manufacturability, which demands component simplification to reduce the complexity and cost. Component simplification also help to minimize the component interdependencies between each other that directly affect minimizing product complexity. This component simplification process contributes to reducing assembly lead time.

5. Reduction of product development complexity: perspective from modular design approach and component interface

5.1 Effect of modular design strategy to reduce product development complexity

Generic product design processes require suitable product development strategies in order to be flexible. The trend within manufacturing companies is to create as many product varieties as possible to be competitive through attracting more customers (Vickery et al., 2016). To develop such variety depends on the companies' ability to adopt accurate and appropriate product design strategies. In such consequence, designing and developing a module-based product development strategy offers valuable insight for any company (Fixon, 2005). In this module-based product design and development strategy, modules are usually formed depending on the component interdependencies and functionalities. Such interdependencies are worked on as an information exchange between components and can be in the form of functionality, energy, force, etc.

The information exchange or dependencies between the components in a product need to be managed efficiently with the objective to reduce product development complexity. This complexity can be managed by reducing the number of feedback loops and forming the optimum number of modules necessary to develop the modular products. In modularity, the modules are used to create new variants by mixing and matching, which is the pre-requisite for gaining mass customization (Shamsuzzoha and Helo, 2011).

A modular design approach offers the best configuration of components and works as a key process feature to promote continuous improvement (Upton and McAfee, 2000; Cabigiosu et al., 2015). It also reduces complexity in processes that contribute to reducing the production costs. Modular architecture enhances the processing flexibilities of machines and brings agility to the manufacturing system. This strategy derives product variants for specific market segments by either adding, removing, or replacing single or multiple modules (Eppinger, 1991; Martin and Ishii, 2002). Modular design therefore brings an important competitive advantage for firms and provides benefits by reducing product design effort and time-to-market (Jacobs et al., 2007; Wurzer and Reiner, 2018; Gupta et al., 2018).

5.2 Effect of components interfaces to reduce product development complexity

Designing component interfaces within a product considers an important concern to reduce product development complexities. It acts as an aid to structure a product's components according to its functionalities. Based on the interface design, functionality of an individual component can be improved. This interface design directly influences product development decisions, whether it will be an integral or module-based product. It also affects the complexity of the product during the assembly process (Tee, 2019).

Before starting a component design, the designer should have a thorough understanding and knowledge of the proposed product. This component interface is used to have one component interact with other to enhance the functionality of the finished product. In order to develop a module-based product, this interface design plays a critical role in design theory (Shamsuzzoha and Helo, 2011). Efficient interface design not only reduces the product development complexity, but it also eases component maintenance and reliability in general (Ulrich, 1994, 1995; Jose and Tollenaere, 2005; Sosa et al., 2004, 2007; Lakemond et al., 2007).

The level of dependency between one component interfaces with another also triggers the formation of modules within a product. More dependency results in tighter modules, while a low level of dependency results in loosely formed modules. Such configuration of module structures contributes to the product-related complexity. Often, it is necessary to minimize the number of component interfaces within modules. This principle restricts the total number of components within a module, which influences a reduction of complexity within a module. It is always recommended to optimize the component numbers within a module (Vickery et al., 2016). It is better to have smaller size modules within a product or product family than a larger size to improve assembly ability and maintenance and to reduce manufacturing complexity.

The design of a component interface also supports product innovation, whether it is incremental innovation or radical innovation. By redesigning the component interface, it might be easy to develop a new product with added functionality. From time to time, product designers need to reexamine the design of the component interface of an existing component and perform any necessary upgrades in order to develop more innovative products (Ulrich, 2003). There should be a scheduled design review of component interfaces within manufacturing companies to develop innovative products that invite better customer attraction, which leads to an added financial benefit (Dereli et al., 2008; Moon et al., 2015; Bonvoisin et al., 2016).

6. Modular product development: complexity and associated drivers

Managing a product development process successfully is considered as an important parameter for business success. It is, therefore, a prime concern for manufacturing companies to efficiently manage their product design and development philosophy. However, it is often not an easy task to manage product development processes. Many challenges arise that are caused initially by the overall design strategy and several known and unknown factors, commonly known as drivers within a company. With respect to the product development perspective, it is seen that a modular design strategy behaves comfortably over an integral design strategy (Duclos et al., 2003).

In a modular strategy, it is easier to manage each module separately through the entire value chain (Pero et al., 2015). If the module cannot be manufactured or assembled 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' surveys (Banker et al., 1990). On the other hand, if the design strategy is an integral principle, then it might create extra complexity in the value chain in order to manage the production properly. This is due to the nature of components, which are highly dependent on each other and cannot easily separate. This integral design issue also brings extra pressure in terms of repair and maintainability (Carlborg and Kindström, 2014).

In addition to design strategy, there are several factors commonly known as drivers, which influence product development complexity. Based on such characteristics, the drivers of product development complexity can be divided into internal complexity drivers, external complexity drivers, and interfacial complexity drivers. Internal complexity drivers are defined as the factors' effect on product development internally to the organization, while, external drivers are associated outside the organizational boundary. The interfacial complexity drivers are the drivers, which are interfaced between component suppliers and customers and exist between internal and external complexities.

All major drivers for product development complexities were collected after an intensive literature review, which is outlined in Table 1. All the associated complexity drivers for product development are classified as internal, external, and interfacial complexities. From Table 1, it can be seen that internal complexities are mainly product development strategies, external complexities are associated with things that facilitate the product development processes in order to be profitable, and interfacial complexities are mostly related to the component suppliers.

Table 1: Major drivers of product development complexity

Type of product development complexity	***Major drivers of product development complexity***
Internal complexity	• Information exchange (Shamsuzzoha and Helo, 2011)
	• Number of product variants (Banker et al., 1990; Lampon et al., 2017)
	• Product innovation (Loch et al., 2003; Nepal et al., 2012)
	• Operational processes (Vickery et al., 2016)
	• Planning and scheduling (Isik, 2010)
	• Knowledge and expertise (Gualandris and Kalchschmidt, 2013)
	• Resource scarcity (Wilding, 1998; Suh, 2005)
	• Organizational level (Wilding, 1998)
	• Inventory management (Sivadasan et al., 2009; Isik, 2010)
	• Marketing and sales promotion (Wilding, 1998)
	• Organizational culture (Lamming, 1996)
External Complexity	• Measuring customer satisfaction (Shamsuzzoha and Helo, 2011)
	• Transportation and logistics (Sivadasan et al., 2009)
	• Business competition (Wilding, 1998)
	• Technology diffusion (Koudal and Engel, 2007)
	• Demand fluctuation (Isik, 2010)
	• Technology transfer and management (Manuj and Sahin, 2011)
	• Product retirement and recycling(Banker et al., 1990)
	• Government rules and regulations (Lubarski and Pöppelbuβ, 2017)
	• Maintaining standard practices (Isik, 2010)
	• Complexity in process synchronization (Wilding, 1998)

	• Interoperable technology (Serdarasan, 2013)
	• Number of suppliers (Manuj and Sahin, 2011)
Interfacial Complexity	• Suppliers locations (Serdarasan, 2013)
	• Customer segments (Pathik et al., 2007; Manuj and Sahin, 2011)
	• Company culture (Vachon and Klassen, 2002; Pathik et al., 2007)
	• Complexity in process synchronization (Wilding, 1998)

7. Evaluation of the product development complexity: a case example

Keeping in mind the objective to assess the overall KPIs of modular product architecture, a case company was selected. The company is a market leader in the energy business. The product selected from the case company is an engine used to produce electrical energy. There are two main types of product development activities within the case company, the development of standard engine projects and customer-specific engine projects. In the latter stage, the standard engine is tailored to fit the needs of a specific customer. The objective of studying this company was to analyze its existing product architecture in order to identify its level of modular product architecture and to recommend future actions for improvement. One of the standard engine development projects was studied with the objective of analyzing its modular product architecture KPIs.

In order to conduct this case study, the necessary data was collected by asking relevant questions of the product designers, supervisors, project managers, and operators. All the face-to-face interviews were conducted with experienced managers and decision-makers at different levels within the company. In addition, several meetings/workshops were organized with the company's management personnel to collect the required data. The company's design database was also used to collect the data. Moreover, the authors were permitted to access additional documents related to the engine project (e.g. product documentation, process descriptions). The data collected from the specific engine project contained various important pieces of information, such as number of components, component interdependencies, number of component interfaces, and strength or level of dependencies.

The data collected from the case company's product was then analyzed using the DSM tool. This tool helps to study the engine's product architecture and to identify the possible modules. The studied engine consisted of 228 components, which were then populated within the DSM tool in order to identify the modules. The modules were developed based the interdependencies among the 228 components. The interdependencies among the components were marked with '1' for high dependency, '2' for medium dependency and '3' for low dependency. The dependency termed as high is considered situations where changing one component directly affects other associated components; medium dependency means the changes do not directly affect other components but indirectly affect them. Low dependency is considered situations where changes to one component have almost a negligible effect on other components.

Based on the dependency levels, all 228 components of the case company's product were populated within the DSM tool, as displayed in Figure 2. Figure 3 displays a closed-look screenshot of some of the interdependencies of the studied engine's components. The red, yellow, and green colors represent the high, medium, and low dependency levels within the components in Figure 3, respectively.

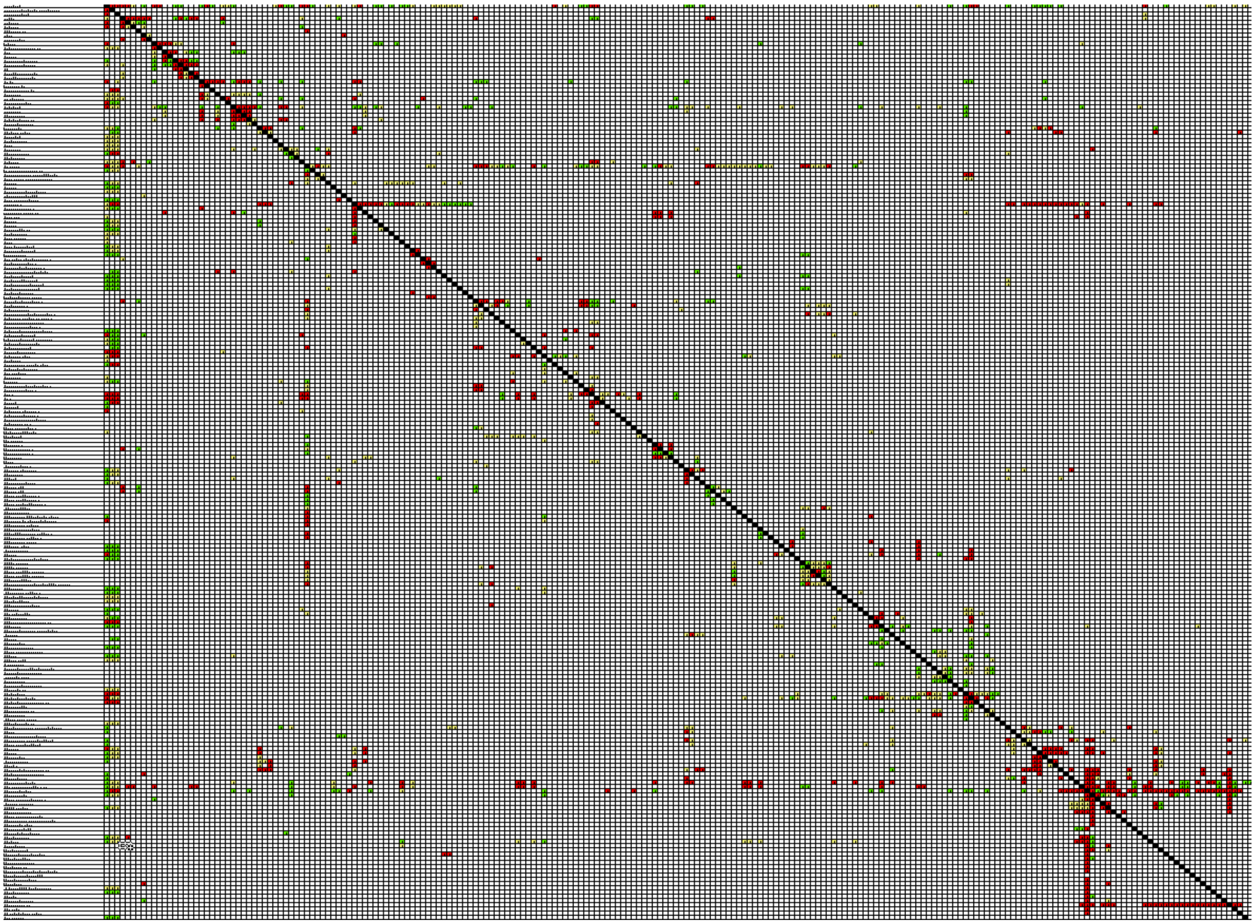

Figure 2: Display of component interdependencies within the case company’s product

5		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	3
6	1! Engine block		3	3	3	3	2		1		3	3			1	1				1	3	1		2	2	1					
7	2! Drilling of engine block for flexible mounted engine	3																													
8	3! Drilling of engine block	3																													
9	4! Crankshaft	2				3	3	3	3	3					1	3	1	3	3					3							
10	5! Main bearing	3			3		2	1	1															1							
11	6! Thurst bearing	3			3	2			2																						
12	7! PTO-shaft equipment																														
13	8! Flywheel									2																					
14	9! Fitting screws fo flywheel				3				3																						
15	10! Cylinder liner	3										3	3	3	2	2										3					
16	11! Cylinder liner fastening equipment	2	2	2							3																				
17	12! Piston										2			3	3		2	1	1							1	1	1			
18	13! Piston ring set										2		3																		
19	14! Connecting rod upper part	1									1		3	1		3	3	1	1												
20	15! Connecting rod lower part	2			2						1		1	1	3		3	3	3												
21	16! Shim										1				3	3															
22	17! Big-end bearing upper half				2											3	2		3												
23	18! Big-end bearing lower half				2											3	2	3													
24	19! Camshaft	3		2							1										3	3	3	3		1	3	3	3		1
25	20! Bearing for camshaft																			3											
26	21! Bearing cover for camshaft		3	3																											
27	22! Valve tappet	2	2	2																3	2					2	2	2	2		1
28	23! Intermediate gear	2	2	2	2															3	2				3						
29	24! Bearings for gear wheels	3	1	1																											
30	25! Cylinder head	3	2	2							2	1	1							1			1				3	3	3	3	1
31	26! Inlet gas valves												2							3			2			3		3	3		
32	27! Exhaust gas valves												2							3			2			3	3		3		
33	28! Cylinder head equipment										2									3			3			3	3	3		2	
34	29! Cover for indicator valve																									1			2		

Figure 3: Close look screenshot of some of the component interdependencies within the case company's product as 'engine'.

All the interdependencies of the 228 components as displayed in Figure 2 are partitioned following the clustering algorithm within the DSM tool. The partitioned DSM with identified modules or clusters are displayed in Figure 4. From Figure 4, it can be seen that the product architecture of the case company's product (engine) is highly integrated and complex in nature. This complex structure developed due to the high interdependencies among the components. From Figure 4, it is observed that three large modules are developed encompassing one with the other, which clearly indicates a high level of complexity within the engine's architecture. This complexity level can be eliminated or at least reduced by redefining the existing engine's architecture.

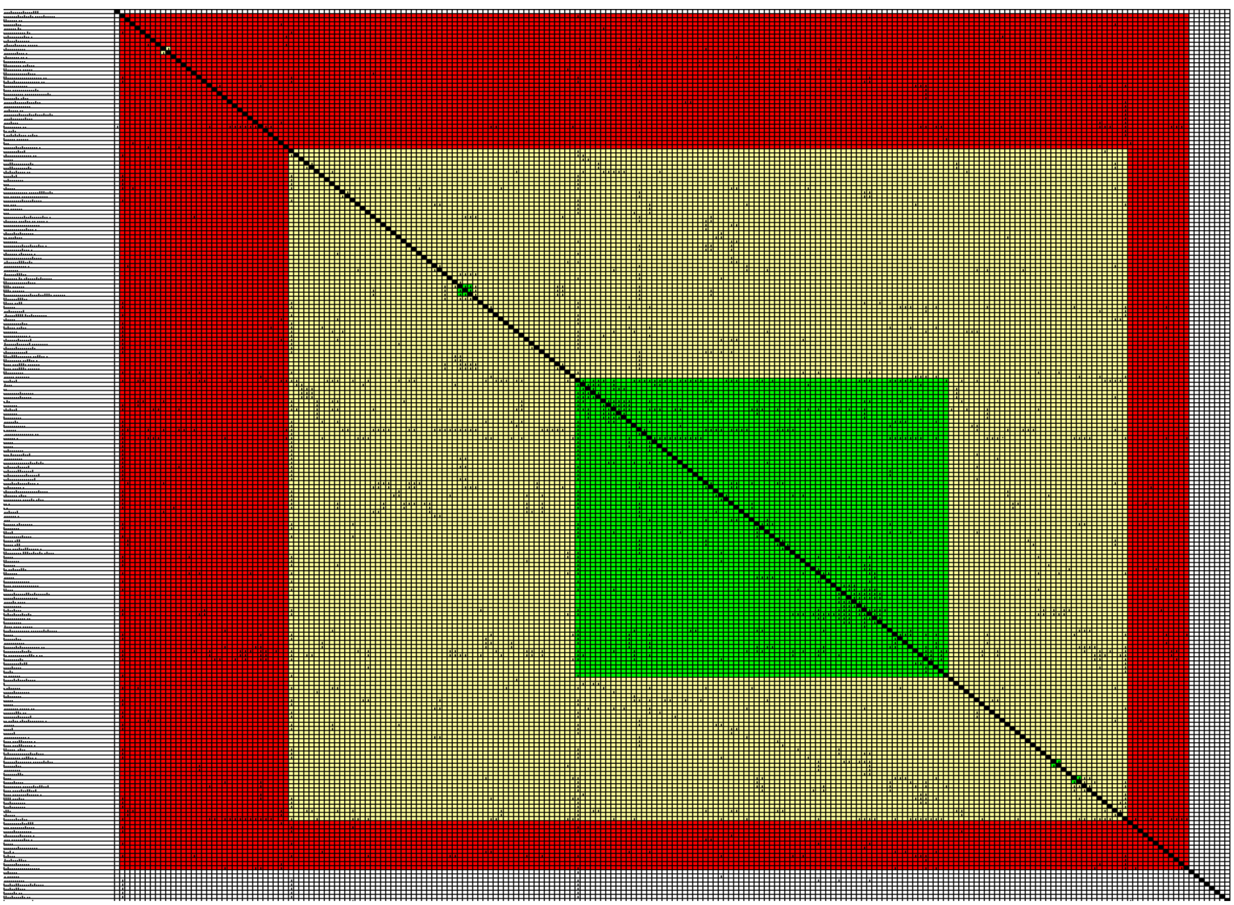

Figure 4: Display of component interdependencies within the case company's product

In order to reduce the level of complexity within the engine's architecture, all the medium and low-level interdependencies among the components were removed and repartitioned in the DSM. The new partitioned DSM only considered the higher dependency marks. The resultant modules are displayed in Figure 5. From Figure 5, it can be seen that four modules were formed with different sizes. Out of the four modules, two modules consisted of two components each, whereas the other two consisted of seven components and 75 components. Out of these four identified modules, three modules consisted of two, two, and seven components, respectively. These components are comfortably manageable. The rest modules consisting of 75 components are displayed as clearly complex with highly integrated components.

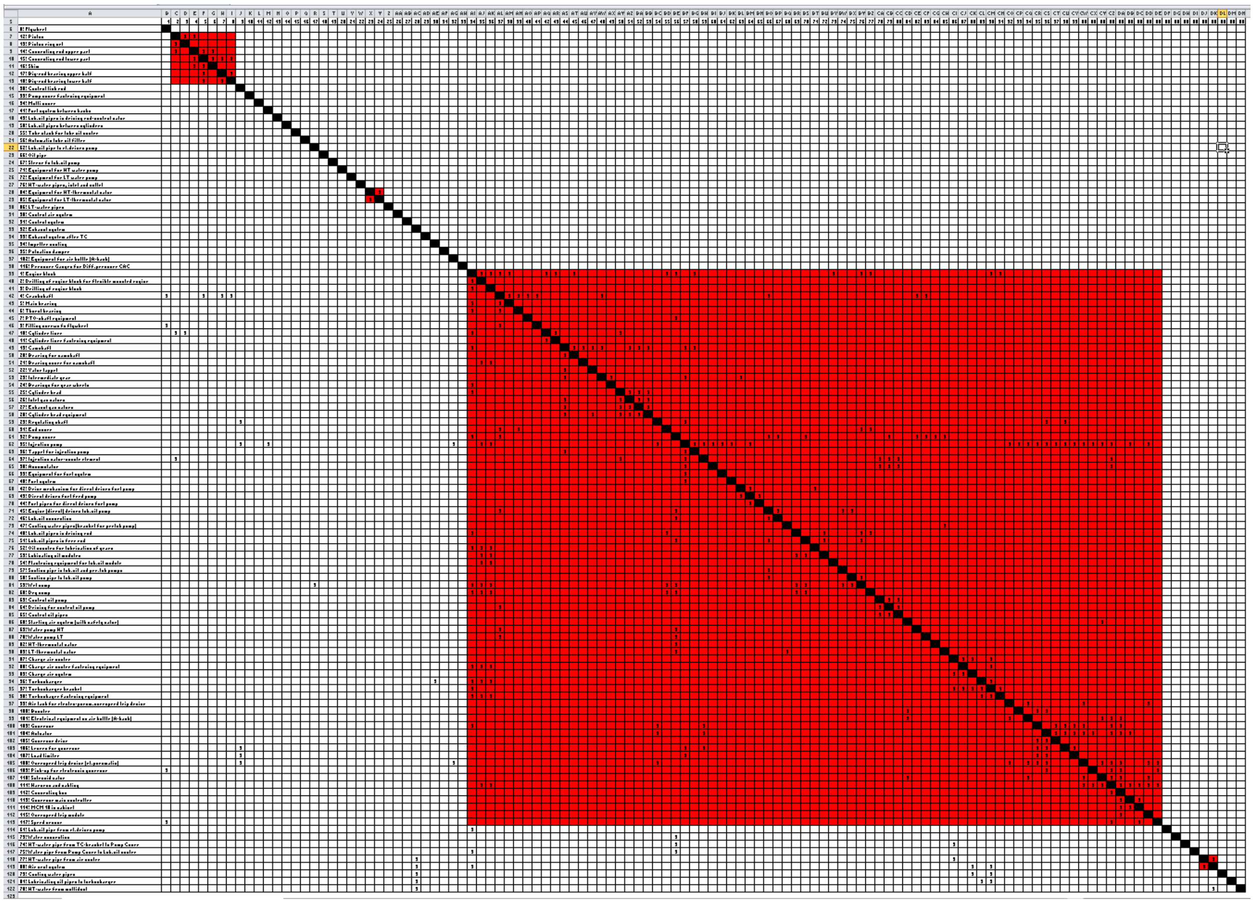

Figure 5: Display of component interdependencies within the case company's product

The largest module, which consisted of 75 components, often shows difficulties in managing it with respect to design and maintenance perspectives. In case of the design perspective, if updates or changes to any component with this module are needed, it would be difficult and cumbersome for the maintenance engineer to do that. On the other hand, if this module can be broken into several smaller modules by revisiting its architecture, then it will offer better maintainability and be easily manageable. During this revisiting process, each of the components within the module need to be rechecked one by one to reduce their dependency on other components. This effort might require a redesign of the component, or it is possible that more than a single component can be grouped together as a single component with accompanying functionalities.

In order to split the largest module into smaller and manageable ones, it is necessary to reinvestigate the component interdependencies and to try to reduce the dependencies as much as possible. It is therefore clear that only the modules developed with a reasonable number of components can offer a reduced product development complexity. At the end of this study, the outcomes were discussed with the company's management personnel to revisit the product architecture to develop smaller and more manageable modules. Such smaller sized modules offer the company an easy assembly ability and maintainability with reduced cost.

8. Managerial implications

Product architecture in a company plays a crucial role in developing faster products with lower costs. Proper selection of the product architecture helps organizational managers reduce the associated product development complexities through component design, selection of component interfaces, number of components, component interdependencies, dependency levels, etc. Based on the product architecture, whether it is integral or modular, managers need to consult with the designers to proceed to the next stage to develop the product. In addition, managers also need to select the suppliers based on the product architecture from where necessary components or modules will be supplied to the production site.

In case of modular product architecture, important insights can be provided to the organizational managers to help them deal with the interdependences across organizational and functional boundaries. In particular, it is required to show how component interdependencies impact product design interfaces. An ideal architecture is an architecture that partitions the developed product into authentic and useful modules. In successfully designed modules, products and components can be easily updated on regular time cycles, which contributes to achieving wider product variety with extended market opportunities. Such developed modules can be easily updated or removed as they wear, and some can be easily swapped to gain added functionality. In addition to product complexity, organization managers also need to focus on supply chain management, which is an integrated part of the product development process. If the product architecture is simple and clearly defined, then each of the components and their functionality are easy to handle within the supply chain too. Clearly defined architecture can ensure advanced supplier selection process that triggers a plan for the required transportation and logistics support. In cases of modular product architecture, organizational managers can select and order the required modules from the suppliers based on their skills and experience (Jung and Simpson, 2017). Modular product architecture also supports managers in reducing safety stock by delaying product differentiation or late customization. From this strategic shift, managers can be more capable of gaining economic benefits by sharing the risk pooling and postponement strategies (Piran et al., 2016).

9. Conclusions and future research directions

Due to changes in global business nature, customers are getting increasingly demanding about their products. They expect their products to be acquired with reduced cost, higher quality, more safety, and easier maintainability and assemble ability. Also, in today’s market place, product life cycles are getting shorter and shorter, forcing manufacturing companies to develop their products to fit the majority of customers’ needs or expectations. Customers are also expecting a higher number of product variants to fulfill their daily needs. To cope with such higher levels of product variety and lesser time-to-market requirements, companies need to make the right decisions at the beginning of their product development process. One of the most important decisions in the product development process is to select its architecture. The product’s architecture can be used as a guideline to design and develop an efficient and quality product that meets customers’ needs (Martin and Ishii, 1996; Shamsuzzoha, 2011; Piran et al., 2016).

Product architecture is intrinsically related to the complexity of a product, as discussed within the scope of this research. Through defining the product architecture efficiently and elaborately, it is possible to eliminate or significantly reduce product development complexity. The complexity related to product design and the development process can be in various formats and types, such as design strategy, assemble ability, maintainability, availability, etc. (Lambert and Cooper, 2000; Jung and Simpson, 2017). The factors associated with product development complexity are directly related to the number of components, number of interfaces, dependency of components with each other, etc. It is therefore critical that the product designer design the product architecture efficiently, which may contribute substantially to reducing product complexity and its related activities such as manufacturing, assembly, and managing the supply chain.

This research considered the modular product design philosophy, where various KPIs for product architecture such as number of components, number of interfaces, interdependencies between components, etc. are identified and analyzed with respect to product complexity. The KPIs associated with product architecture were analyzed by implementing the concept in a case company's product. From the study, it was identified that the architecture of the case company is highly integrated, and it was recommended that they revisit the product architecture to make it as modular a design as possible by redefining components interfaces, introducing common and standard components, adopting a modular platform, and more.

The two research objectives were validated by investigating the relevant literature and case company's product architecture. The first research objective was met by investigating the product architecture of the case company. From this exploratory case study, it was noticed that product architecture affects the product development process by increasing or decreasing the product complexity. The analysis shows that the case company's product architecture is highly integrated in nature, which restricts it's assemble ability, maintainability, and innovation. This integral architecture negatively affects the product's rapid improvement, which is done by redesigning the component structure, which is quite difficult, as any changes in components impact neighboring components that might need to be redesigned as well. This consecutive redesign increases the costs and the complexity. On the other hand, a modular architecture may improve the overall product design, if necessary, by redesigning or replacing the modules based on the customization need.

The second research objective was met by identifying the associated KPIs and drivers responsible for product development complexity with respect to product architecture. The impact of product architecture on modular product design and development was discussed within the scope of this research. This research studied the idea that designing an appropriate product architecture can reduce product development complexity. The fundamental drivers for modular product development complexity were also identified within the objective to define and manage them efficiently to reduce the complexity. The drivers are categorized as internal, external, and interfacial. Any company that wishes to measure its modular product development complexity level can use the identified drivers, and any required steps can be taken to eliminate or reduce such complexity issue (Martin and Ishii, 1996).

In future research, more case companies will be studied with the objective to generalize the impact of product architecture on complexity related to the modular product development process. Additionally, the identified drivers are to be implemented in multiple case companies with the objective to study their effects on generic product development complexity. Furthermore, research will also continue to investigate the impact of real-time information exchange on product development complexity.

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