

RESEARCH PAPER

Identification and analysis of the driving factors for product modularity by interpretive structural modelling

Ahm Shamsuzzoha¹, Sujan Piya²¹University of Vaasa, School of Technology and Innovations, Vaasa, Finland.²Sultan Qaboos University, Department of Mechanical and Industrial Engineering, Muscat, Oman.

How to cite: Shamsuzzoha, A. and Piya, S. (2020), "Identification and analysis of the driving factors for product modularity by interpretive structural modelling", *Brazilian Journal of Operations & Production Management*, Vol. 17, No. 4, e2020909. <https://doi.org/10.14488/BJOPM.2020.041>

ABSTRACT

Goal: The purpose of this study is to identify the driving factors that affects modular product design and development and to determine the contextual relationships between the identified factors.

Design / Methodology / Approach: This research study adopted both qualitative and quantitative methodologies. In qualitative part, an extensive literature review is conducted along with interviews with the experts experienced in product design and development in order to identify and sorted out the driving factors for product modularity. In quantitative part, all the identified factors were analyzed through Interpretive Structural Modeling (ISM) method. MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (cross-impact matrix multiplication applied to classification) analysis is carried out to determine the relative driving and dependency power of the factors.

Results: The contribution of this paper is the identification of the factors associated with developing a modular product. Through the use of ISM diagram, the identified factors were clustered into different layers based on their driving and dependency characteristics. The ISM diagram also presented the relationship between one factor over others and the reason for such relationship. Such a diagram offers decision maker better visibility on the factor that they need to consider or strategy they need to implement to improve their modular product design and development architecture. The results from this research study encompass organizational managers for handling multiple design views, controlling design related interfaces and ranking the status and progress of product modularity and design completeness.

Limitations of the investigation: The outcomes from this research may not be generalize sufficiently due to subjectivity of the interviewers.

Practical implications: The study outcomes support product designers to optimize their product development processes, especially to develop modular products. The presented methodology can be used extensively used by the product designers/planners/managers to find the driving factors related to modular product design and development.

Originality / Value: The originality of this research study is to deploy the ISM approach, which can be used by the organizational managers and/or product designers to plan product development strategies. Such strategies help to them to make necessary decisions on resources allocations.

Keywords: Product Modularity; Driving Factors; ISM; Mass Customization; Expert Opinions.

Financial support: None.

Conflict of interest: The authors have no conflict of interest to declare.

Corresponding author: ahm.shamsuzzoha@uwasa.fi

Received: 7 Dec 2019.

Approved: 23 Aug 2020.

Editor: Osvaldo L. G. Quelhas.



This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1. INTRODUCTION

Global manufacturing industries are undergoing a major shift from the traditional manufacturing process to the flexible manufacturing process. This flexibility offers manufacturing companies to rapidly respond to all changes in the global market environment by rationalizing its manufacturing facilities and producing a large variety of products at a lower cost and time. However, it is not an easy task to develop product variety with limited resources. To stay competitive in today's market segment, it is crucial to develop product variety due to the increased level of customization. Global customers are more selective than ever, which creates extra pressure on manufacturing companies to develop variety of products. In such circumstances, modular product development and product family strategies provides a way to produce a variety of products to satisfy mass customers (Baylis et al., 2018; Zhang et al., 2019; Loureiro et al., 2020). The modular product design and development strategy provides crucial agile manufacturing through the combination of distinct building blocks (modules). This strategy is receiving serious attention in the current manufacturing processes (Colombo et al., 2020). Modular product design and development process refers to a product, the components of which fulfills various functions through the combination of distinct building blocks or modules (Peng and Mu, 2018; Sun and Lau, 2019). The modules are the combination of certain components allowed by the specified standard interfaces of a modular product. Through the combination of mixing and matching of modules, a potentially large number of different products can be generated in a modular product architecture. Such a combination of modules offers distinctive product variants with different functionalities, features and/or performance levels of the developed products to satisfy major customers' requirements successfully (Shamsuzzoha et al., 2018; 2020; Kim et al., 2020). Therefore, a modular product development strategy is an important source of strategic flexibility.

Even though adoption of modularity in the product design and development process is a way forward to survive in today's competitive business environment, (Clemente et al., 2019; Kim et al., 2020), it is not an easy approach to adopt. This is due to the reason that so many inherent factors affect the design decision to adopt product modularity. To identify such responsible factors of product modularity and their interdependencies with each other an interpretive structural modeling (ISM) tool is implemented in this research study. TISM is an interactive learning process in which some unique and straightforwardly related factors are organized into a model which is concise enough to get the overall view of a complex system. It is the structural depict of a convoluted problem or issue in a sophisticatedly structured pattern. ISM also identifies the priority level of factors and shows the directions of the elements (Agrawal et al., 2019; Piya et al., 2020a; 2020b).

Based on the above requirements, this study focused on two objectives, which are tried to fulfill within the scope of this research study. The objectives are stated as below:

- (1) To identify and investigate relevant driving factors and their interrelationships to adopting product modularity;
- (2) To formulate necessary guidelines to develop successful modular product.

The rest of the paper is organized as follows. Section 2 highlights existing literature related to modular product development strategy, while Section 3 outlines the research methodology along with the description of ISM method. Various driving factors that affects to develop modularity are collected from literature review, and are presented and briefly explained in Section 4, whereas, Section 5 illustrates the analysis of modularity factors using ISM. Practical importance of this research study is presented in Section 6 and necessary discussions and conclusions on research outcomes are stated in Section 7.

2. LITERATURE REVIEW

Nowadays, product modularity is a buzzword in the industrial arena. It is considered as an important principle of product design and development architecture. Product modularity can be considered as the relationship between a product's functional and physical structures, where there is a one-to-one or many-to-one relationship between the functional and physical

structures. This concept consists of decomposing a system into independent parts or modules that can be treated as logical units (Bruun et al., 2015). The basic idea of modularity is to break the system into discrete modules through ensuring that the modules can interchange with each other and provide well-defined interfaces. Decomposition, standardization and interchangeability are the critical issues for product modularity. The developed modules enable to form the basis for the configuration of product families. The configuration of product families offers more customized products at lower costs. Product customization through make-to-order production policy is a growing trend in the market to attract customer and satisfy their needs (Piya et al., 2016).

Product modularity is the best approach to deal with the product development complexity (Baldwin and Clark, 2000). Ulrich and Tung (1991) defined modularity in terms of product design, which is based on two categories: (1) similarity between the physical and functional architecture of the design and (2) minimization of identical interactions between physical components (Gershenson and Prasad, 1997). Modularity has several benefits including cost optimization, reduced lead time, imparting a large product variants, simplicity of product analysis, upkeep, upgrading, renovate and reuse, even often increasing product life cycle (Pahl and Beitz, 2013).

Modular product development strategy focuses to produce an independent, standardized and interchangeable product to achieve added functionalities at lower cost (Zhang et al., 2019; Loureiro et al., 2020). The strategy also supports parallelism in design activities and collaboration between a diversity of disciplines in companies. It has been considered as a good design practice in the concurrent engineering area. Distributed collaborative design of modular products supports to respond quickly in changing market demands (Kim et al., 2020). Such an environment is used to create, utilize and manage product development systems to enhance communication and cooperation among partner companies in an integrated and coherent fashion. Therefore, before designing modular products, it is important to develop necessary knowledge and then manage information flow within the company and among the partner. This knowledge development process specifies relevant components and their interactions. In essence, a modular design must be based on knowledge about relevant components specifications.

Modular design plan has an explicit direction in the process of sustainable product development. Increasing concerns about environmental impact have driven companies to reconsider product design processes from the sustainability point of view. It has attracted significant attention from both academia and manufacturer to blend the concepts of modularity and sustainability (Rennpferdt et al., 2019). It has been used to integrate different design parties in a single platform and supports to construct common or standard parts for creating product varieties. This standardization of parts enhances the controllability and observability of testing, thus reduces complexity in companies, especially in design engineering.

In order to be successful in modular product development, it is crucial to identify the associated factors that drives product modularity. These factors can be defined as the criteria's behind modularization along the entire product life cycle (Erixon et al., 1994; 1996). Examples of modularity factors can be as component interfaces, standardization, manufacturability, assemble ability, information exchange, product design knowledge, etc. The factors that drives the product modularity and their interrelationships or interdependencies among the factors can be analyzed using the interpretive structural modeling (ISM) method (Malek and Desai, 2019). Besides, the use of ISM method, the relationship among the factors can be analyzed through the Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) method (Rajagopal and Ramasamy, 2020). This cross-impact matrix multiplication method used to detect and to scrutinize the relative driving and dependency power of the identified factors (Ansari et al., 2013).

3. RESEARCH METHODOLOGY

This research study is conducted by adopting both qualitative and quantitative approaches. In the qualitative part of the study, a rigorous literature review and experts opinions were collected to identify and prioritize the factors responsible to develop modular product. During literature survey several keywords such as product modularity, variables for modular product, modular product design, limitations for product modularity, etc., were searched to find out the drivers that affecting product modularity. The reviewed articles were collected from various publication databases such as web of science, JSTOR, PubMed, EBSCO, ProQuest, etc., from 1994 to 2020. From the literature, the most critical and commonly available variables were considered for this study.

In case of experts opinions, in total 8 experts from various business domains (energy, electronics, furniture and ship industry) were interviewed to prioritize the identified factors as done through literature review. In addition to the interviews with the experts, three consecutive brainstorming sessions were arranged with the product designers/planners in three case companies, where the collected drivers for product modularity were discussed. At the end of such sessions, 18 factors were selected from the collected 27 factors based on the experiences of the experts and criticality and commonality of the factors. Table 1 highlights the working sectors, designations and working experiences of the experts. Based on the extensive literature survey 27 factors were identified, which were then verified and analyzed by the experts attended the three brainstorming sessions and 18 factors were finally selected as the most important factors that impacts over the decision to develop the modular product.

Table 1. Demography of experts for brainstorming sessions

<u>Business sectors</u>
- Energy industry: 39.5%
- Electronics: 35.5%
- Furniture:15.5%
- Ship industry:9.5%
<u>Designation of the experts</u>
- Product manager: 40.5%
- Product designer: 22%
- Transportation manager: 14.5%
- Managing director: 23%%
<u>Working experience of the experts (in years)</u>
- 10 to 15: 50%
- 16 to 20: 35.5%
- Over 21: 14.5%

In the quantitative part of the study, identified and prioritized factors were analyzed by adopting an interpretive structural modeling (ISM) method. The ISM is a well-known methodological approach for identifying the relationships among factors or variables of a specific problem. This method has been deployed by many researchers and practitioners to find out the interrelationships among various factors (Attri et al., 2013). At this approach, it is necessary to first identify the factors associated with the issue or problem. At the second phase, contextually relevant subordinate relation is chosen, from which a structural self-interaction matrix is eventually developed depending on the pairwise comparison of the identified factors. Afterwards, a reachability matrix is achieved after checking the transitivity of the reachability matrix. Finally, a matrix model known as ISM is derived which is achieved after partitioning of the identified factors.

The ISM method first asserted by Warfield in 1973, is the most effective method to deal with complex issues (Ansari et al., 2013). According to Vinod et al. (2019) and (Moberg et al., 2002), ISM concept is based on the utilization of experts’ practical experiences to establish a structural model and show the elements hindering the execution of a specific system. ISM method demonstrate whether and how the factors are related to each other in a structural way (Mandal and Deshmukh, 1994). The procedural steps for developing an ISM model are shown in Figure 1 (Eswarlal et al., 2011). Each of the steps are also briefly clarified as follows.

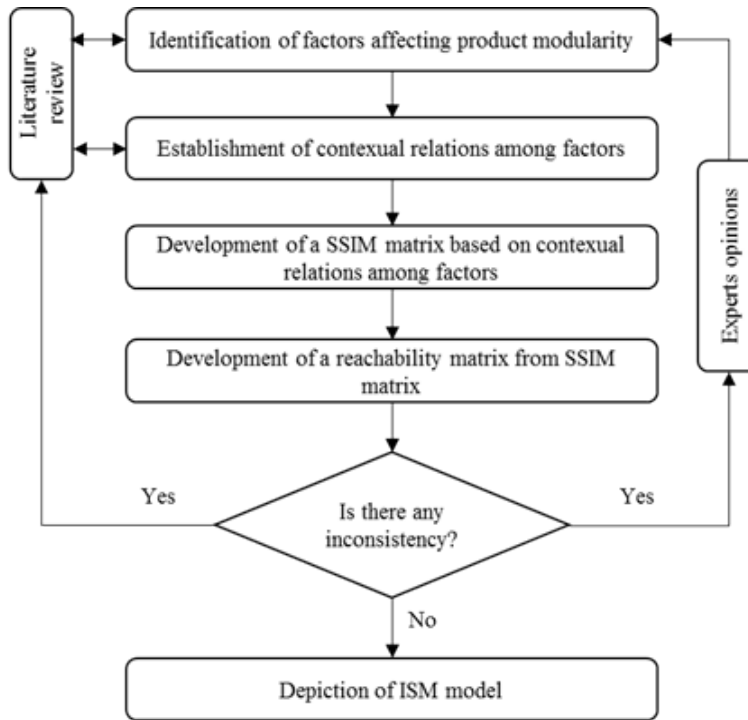


Figure 1. ISM procedural steps

Step 1: Identifying the factors

The factors responsible for adopting a modular strategy needs to be identified through a careful review of the literature and expert opinion.

Step 2: Establish and interpret contextual relationships

The contextual relationships need to be established among the identified factors of interest. At this step, a structural self-interaction matrix (SSIM) is developed based on the interpretation of contextual relationships between the factors.

Step 3: Develop an initial reachability matrix

A reachability matrix is developed, which is formed from the pairwise relationship (SSIM) between the identified factors. This relationship is transformed into a binary matrix 1 and 0 (yes =1 and no = 0).

Step 4: Develop final reachability matrix

A final reachability matrix is developed from the initial reachability matrix, which is formed by identifying the transitivity factors using transitivity theory. The transitivity theory states that if factor A is related to factor B and factor B is related to factor C, then factor A is also related to factor C. Both the driving and dependency power of each of the identified factors are extracted from this matrix.

Step 5: Level partitions in the reachability matrix

Level partition is done by using the reachability, antecedents and the intersection sets. From these sets, all the factors are leveled. The leveling process is done iteratively and continued until factors at all levels are determined.

Step 6: Develop the digraphs

A directed graph, which is an outcome of ISM model, is drawn based on the contextual relationship of the identified factors within the reachability matrix and using the transitivity links. The factors are arranged according to the levels and the most influential relations are plotted in the digraphs. Level 1 is displayed at the top of the digraph, which follows down by the other levels sequentially. The process is basically conducted on the basis of an interpretive logic from the knowledge base of the influential relations.

Step7: Validate the digraph and construct the ISM model

The represented relations in digraphs are to be validated using a panel of experts. The digraph representing prominent relations of the ISM model as already established is checked for its conceptual inconsistency and essential steps are taken to reconstruct the model. The relationships within the ISM model is then translated with statements.

The objective of using ISM method is to visualize and to analyze the relationships among the identified factors responsible for developing modular product. Finally, an MICMAC analysis was done to detect the relative driving and dependency power of the identified factors over modular product development strategy.

4. DRIVING FACTORS CONTRIBUTING TO PRODUCT MODULARITY

Every decision making process goes through the consideration of some factors. These factors have a direct or indirect impact on the decision. Similarly, to adopt a modular product development strategy, there exist a plethora of factors. The factors are collected within the scope of this research study through an extensive literature survey and experts’ opinions in the field of modular product design and development. The driving factors that affect the decision making process of adopting modular product design and development strategies are summarized in Table 2. In addition, corresponding references from the literatures of each of the identified factors are also cited accordingly.

Table 2. Identified drivers of product modularity based on literature review

Factor	Driving factor	Relation to product modularity
F1	Component dependency	A higher level of component dependency restricts to develop modular product and vice versa (Gershenson and Prasad, 1997; Sosa et al., 2004; Pashaei and Olhager, 2015; Mesa et al., 2020).
F2	Standard component	More standard component facilitates product modularity and vice versa (Boothroyd, 1994; Jose and Tollenaere, 2005; Buergin et al., 2018; Wilschut et al., 2019).
F3	Management decision	It is absolutely important to get approval from firms management before proceeding towards modular product development strategy (Singh et al., 2003; Peng and Mu, 2018; Zhang et al., 2019; Hackl et al., 2020).
F4	Customization level	Modular product development strategy also depends on the customization level. More customization triggers more modularity and vice versa (Silveira et al., 2001; Zhang et al., 2014; 2019; Shamsuzzoha et al., 2018).
F5	Manufacturability	Manufacturability affects heavily to develop a modular product. Increased manufacturability promotes modular product design and development strategy (Shamsuzzoha and Helo, 2017; Peng and Mu, 2018).

Table 2. Continued...

Factor	Driving factor	Relation to product modularity
F6	Assemble ability	Modular product design promotes through an increased level of assemble ability. Lower assemble ability limits the modularity level (Salvador et al., 2002; Shaik et al., 2015; Esterman et al., 2020).
F7	Component lead time	More component lead-time restricts modular product development strategy. Lower component lead-time facilitates product modularity (Ulrich, 1994; Gershenson and Prasad, 1997; Buergin et al., 2018).
F8	Component availability	More availability of component expedites the product modularity and vice versa (Shaik et al., 2015; Shoval and Efatmaneshnik, 2019).
F9	Product design knowledge	It is critical to know about the developed product. Product design knowledge enhances product modularity and vice versa (Peng and Mu, 2018).
F10	Inventory management	Modular product development strategy offers less inventory to manage. Developed modules are easily storable to less inventory space (Ben-Daya and Raouf, 1994; Mondragon and Mondragon, 2018).
F11	Information exchange	In every step of the modular product development process, it is necessary to ensure proper and on time information exchange between the design and development related stakeholders to be faster and economical (Moberg et al., 2002; Meissner et al., 2020).
F12	Market demand	Modular product usually attracts more customers due to its usability and maintainability, which ultimately increases the market demand (Zhang et al., 2014; 2019).
F13	Technology & Tools	Advanced and new technology and tools contribute to developing the modular product (Marion et al., 2015; Mondragon and Mondragon, 2018).
F14	Product life cycle	Modular product influences over its life cycle. Extended level of maintainability and replacement option of modules increases the overall product life cycle (Kamali and Hewage, 2016).
F15	Customer awareness	In general, customer awareness is considered as an essential indicator for product modularity. More customer awareness promotes modularity (Servaes and Tamayo, 2013; Zhang et al., 2019).
F16	Component interface	The component interface has a direct impact on product modularity. Properly designed component interface contributes to promoting product modularity (Gershenson and Prasad, 1997; Shamsuzzoha et al., 2018).
F17	Component commonality	More common component, easier will be to develop a modular product with reduced lead-time and developmental cost (Collier, 1981; Buergin et al., 2018).
F18	Product variety	Modular product development strategy offers higher product variety. It is relatively easier to develop variety by interchanging or replacing modules from one product to another (Peng and Mu, 2018; Zhang et al., 2019).

Each of the factors as listed in Table 2 are briefly described below:

Component dependency (F1): Component dependency can be defined as the interdependencies between one component to another one (ElMaraghy and AlGeddawy, 2012). Such dependency contributes to the decision towards a modular product or not (Shamsuzzoha et al., 2018). A high degree of interdependence can be created between components and modules by implementing the strategy of standardizing interface (Barbosa et al., 2017).

Standard component (F2): This type of component follows specific measurement and standard. The standard component can be used successfully to develop a product variety within a family of the product (Efatmaneshnik et al., 2020; Shamsuzzoha et al., 2018).

Management decision (F3): This is an important factor related to top management to decide whether to go for product modularity or not. Management has to ensure that all the necessary resources such as skill, tools, technologies and other logistics support are in place according to the need of a level of product modularization that the company wants to achieve.

Customization level (F4): Modular product development strategy depends highly on customization level. More modular products often support higher customization and vice versa. According to Zhang et al. (2019), product modularity improves customer quality integration through mass customization.

Manufacturability (F5): Generally, modularization of product is done without a complete understanding of its implications on design and manufacturability. Modularity necessitates understanding of various manufacturing processes associated with each attribute of the component (Gershenson and Prasad, 1997). Level of manufacturability of a company indicates whether it is ready to adopt a modular product or not. Ease of manufacturability supports product modularity in general.

Assemble ability (F6): Assemble ability can be defined as the ability to combine different components or modules to form a specific product or family of products. Higher level of assemble ability can be achieved through designing the components/modules interfaces in such a way that offers ease in assembly process with reduced lead-time and vice versa. According to Asadi et al. (2019), in order to improve flexibility, product modularity must be based on a common assembly sequence and module contents in the final assembly across distinct product families.

Component lead time (F7): The time required from receiving an order of a product from a customer to deliver it is known as lead time. It is a critical factor that affects the overall decision process to adopt product modularity. Empirical research by Watanabe and Ane (2004) shows that modular product architecture results into a higher degree of manufacturing agility, which in turn leads to shorter lead time.

Component availability (F8): Availability of component denotes the flexibility or ease of getting any component in the right place on the right time.

Product design knowledge (F9): It is essential to the prospective product designer to know the ins and outs of the developed product. Once the manufacturer modularizes a new product, the developer can design their assigned modules with various ideas. The developer should focus on perfecting their technical knowledge on product design, which is essential to support modularization strategy (Lau et al., 2011).

Inventory management (F10): To save costly storage space, it is critical to managing inventory level optimally. Modular product architecture helps reduce safety stock level, which in turn makes it easier and less costly to manage inventory (Hernández et al., 2015). For modular product design, it is necessary to ensure that required components/modules are available on time during the manufacturing/assembly process.

Information exchange (F11): A proper flow of information can truncate the logistics cost as well as enhance the value of the product to its customers. Exchange of accurate and timely information within and out of the organization is essential to reduce complexity in product development and improve organizational performance (Piya et al., 2017). Lau et al. (2010) has shown that organization that has a high level of product modularity appear to be good at product co-development, organizational coordination and information exchange.

Market demand (F12): As the market demands vary from region to region, it is important that demand from the market should be accurately identified in order to fulfill customers' demands. If there is an error to identify the proper market demand, there is always a risk to reduce profitability and incur a loss. Many companies implement the concept of product modularity to address the growing need for the symbiosis of various technologies and to fulfill market demand (Marshall and Leaney, 1999).

Technology and tools (F13): To survive in today's competitive business world, it is necessary to update/upgrade required technology and tools considering the associated

costs. To develop a modular product, several tools, technologies and methods are essential to support the process of planning, conceptualization and realization of modular products (Breidert and Welp, 2003).

Product life cycle (F14): This is concerned with the study of the degree of acceptance of the product by the market over various time periods. It is the actual study of the time when the product is introduced, when it reaches its peak sale, when it starts falling and when it disappeared. No product can satisfy its customer for an unlimited period of time. The product life cycle can also be described in terms of sales and profit over time. Cebon et al. (2008) argue that product modularization undermines the specific synergies that drive the product lifecycle. Undermining of such synergies has impacts on organizational structure and its economy.

Customer awareness (F15): The ultimate success of an industry depends entirely on the awareness of the customer. The value of the product increases automatically for the manufacturing firms, which are highly aware of their loyal customers. Firms with low customer awareness experience a negative brand value. Sometimes customer awareness can be compensated by advertising costs to a minimum level. Tu et al. (2004) emphasized that the firm should keep close contact with customers and acquire feedback to know their level of product awareness.

Component interface (F16): This is an important factor that concerns to develop a modular product. Depending on the interface design, components can be tightly integrated to form individual modules. Better specified interfaces make the components easy to form the modules as required to develop a modular product (Buergin et al., 2018). On the other hand, poorly designed interfaces create complexity in the product modularity.

Component commonality (F17): More common the components in a product or product family offer a higher level of assemble ability with reduced cost. In the case of product modularity, component commonality affects the overall design decision. The increased commonality of component parts in a product leads to a low level of modularity and vice-versa (Asadi et al., 2019).

Product variety (F18): In order to meet customer demands, manufacturing firms need to produce a lot of product variants. Generally, modular product development strategy offers an opportunity to develop more product variants. However, the pertinent question to the management is to know the number of product varieties to be introduced to meet customer demand and to understand the number of modules required to support the product varieties (Chakravarty and Balakrishnan, 2001).

5. ANALYSIS OF MODULARITY FACTORS USING ISM

At this phase, the identified factors as presented in Table 2, which affect the implementation of product modularity are analyzed using ISM methodology.

5.1 Self-structure interaction matrix

For the analysis of identified modularity factor, the contextual relationships between the factors need to be identified using expert's opinion. The relationships are presented using symbols such as V, A, X, and O. The explanations of the symbols V, A, X, and O are given below:

V = factor i will drive factor j to achieve product modularity;

A = factor j will drive factor i to achieve product modularity;

X = factors i and j will drive each other achieve product modularity

O = factor i and j will not drive each other to achieve product modularity

In this paper, we first develop interpretive logic table based on expert's opinion, the result of which are then presented in Table 3 in the form of self-structured interaction matrix (SSIM). The interpretive logic table demonstrates why or how one factor affects others so that the contextual relationship between the pair of factors can be identified. The interpretive logic table for the factor F1 with other factors of modularity is as shown in Table 4.

The relationships as shown in the table can be explained as an example as follows. F1 (component dependency) as presented in Table 3 drives F10 (inventory management) to achieve product modularity. It means that if there are more dependencies among components, it will increase the inventory level and vice versa. However, this relationship is not reciprocal i.e., F10 does not drive F1 to achieve product modularity. Hence, the contextual relationship between F1 with F10 is "V". Similarly, F9 (product design knowledge) drives F1 (component dependency) to achieve product modularity, meaning that it is important to know necessary design knowledge to develop modular product and the relationship between F1 and F9 is represented as 'A' in Table 3. Again, the relationship between F1 and F16 (component interface) is represented as "X", meaning both the factors are drive each other to develop modular product. In a same fashion, the relationship between F1 and F17 (component commonality) is represented by "O", meaning that both factors are not driving each other to develop modular product.

Similar to the relationship of F1 with other modularity factors as discussed above, we have analyzed the relationships for all other factors using interpretive logic tables. All the pair-wise relationships between F1 and other factors were analyzed and presented in Table 3 as sample. In a similar way, all the 170 pair-wise relationships between all the 18 factors between each others are analyzed and are used to obtain SSIM, which is as shown in Table 4.

Table 3. Interpretive logic table for component dependency (F1) with other available factors responsible to product modularity

Factor (i-j)	Compared relationship	Comparison statement	T/ F	If the comparison statement is true, why?	Relation
F1-F2	F1 → F2	Component dependency leads to standard component	F	-	O
	F2 → F1	Standard component leads to component dependency	F	-	
F1-F3	F1 → F3	Component dependency leads to management decision	F	-	A
	F3 → F1	Management decision leads to component dependency	T	Product development strategy (integral/modular) fully depends on management decision, which also determines the component dependency.	
F1-F4	F1 → F4	Component dependency leads to customization level	T	Increasing level of customization requires more product variety, which ultimately increases the interdependencies between components and vice versa.	V
	F4 → F1	Customization level leads to component dependency	F	-	
F1-F5	F1 → F5	Component dependency leads to manufacturability	F	-	O
	F5 → F1	Manufacturability leads to component dependency	F	-	

Table 3. Continued...

Factor (i-j)	Compared relationship	Comparison statement	T/ F	If the comparison statement is true, why?	Relation
F1-F6	F1 → F6	Component dependency leads to assemble ability	T	More component dependency makes the assemble ability complex and vice versa.	V
	F6 → F1	Assemble ability leads to component dependency	F		
F1-F7	F1 → F7	Component dependency leads to component lead time	T	Increased level of component dependencies needs more time to manufacture and/or assemble a product and vice versa.	V
	F7 → F1	Component lead time leads to component dependency	F		
F1-F8	F1 → F8	Component dependency leads to component availability	F		O
	F8 → F1	Component availability leads to component dependency	F		
F1-F9	F1 → F9	Component dependency leads to product design knowledge	F	If the designer has thorough knowledge of the product to be developed, it is easier to determine the interdependency of the components.	A
	F9 → F1	Product design knowledge leads to component dependency	T		
F1-F10	F1 → F10	Component dependency leads to inventory management	T	If there are more components interdependencies, it is required to maintain a large amount of components inventories.	V
	F10 → F1	Inventory management leads to component dependency	F		
F1-F11	F1 → F11	Component dependency leads to competitor action	F		O
	F11 → F1	Competitor action leads to component dependency	F		
F1-F12	F1 → F12	Component dependency leads to market demand	F		O
	F12 → F1	Market demand leads to component dependency	F		

Table 3. Continued...

Factor (i-j)	Compared relationship	Comparison statement	T/ F	If the comparison statement is true, why?	Relation
F1-F13	F1 → F13	Component dependency leads to technology & tools	F	-	O
	F13 → F1	Technology & tools lead to component dependency	F	-	
F1-F14	F1 → F14	Component dependency leads to product life cycle	T	More interdependencies among components reduce the chance of long product life cycle and vice versa.	V
	F14 → F1	Product life cycle leads to component dependency	F		
F1-F15	F1 → F15	Component dependency leads to customer awareness	F	-	O
	F15 → F1	Customer awareness leads to component dependency	F	-	
F1-F16	F1 → F16	Component dependency leads to component interface	T	The higher level of interdependencies among components increases the chance of more interfaces among the components.	X
	F16 → F1	Component interface leads to component dependency	T	More interfaces among components usually result in higher components interdependencies and vice versa.	
F1-F17	F1 → F17	Component dependency leads to forecasting error	F	-	O
	F17 → F1	Forecasting error leads to component dependency	F	-	
F1-F18	F1 → F18	Component dependency leads to product variety	T	To produce more product variety, there always needs an increased number of components and interdependencies among the components eventually.	V
	F18 → F1	Product variety leads to component dependency	F		

Table 4. Display of structural self-interaction matrix (SSIM)

Factors (i/j)	F18	F17	F16	F15	F14	F13	F12	F11	F10	F9	F8	F7	F6	F5	F4	F3	F2	F1
F1 - Component dependency	V	O	X	O	V	O	O	O	V	A	O	V	V	O	V	A	O	
F2 - Standard component	O	X	V	O	O	O	O	A	V	A	V	O	V	A	V	A		
F3 - Management decision	V	V	V	O	O	V	A	O	V	O	V	O	O	X	V			
F4 - Customization level	X	O	O	X	O	A	X	O	V	A	O	O	A	A				
F5 - Manufacturability	V	O	V	O	O	X	O	O	O	A	O	V	V					
F6 - Assembleability	V	A	A	O	O	A	O	A	O	A	O	O						
F7 - Component lead time	O	A	A	O	O	A	O	A	O	A	O							
F8 - Component availability	O	O	O	A	O	A	A	O	X	O								
F9 - Product design knowledge	V	V	V	O	V	O	V	O	O									
F10 - Inventory management	A	A	O	X	X	O	A	O										
F11 - Information exchange	V	V	V	O	O	O	O											
F12 - Market demand	X	O	O	A	O	O												
F13 - Technology & Tools	V	V	V	O	V													
F14 - Product life cycle	O	O	O	A														
F15 - Customer awareness	X	O	O															
F16 - Component interface	O	O																
F17 - Component commonality	V																	
F18 - Product variety																		

5.2 Initial reachability matrix

The initial reachability matrix as developed from SSIM is displayed in Table 5. In this matrix, a binary matrix (0 and 1) is used based on the following rules:

- If (i, j) entry in SSIM is V, then (i, j) entry in the reachability matrix will be 1 (for instance, cell 1-4), and the (j, i) entry will be 0 (for instance, cell 4-1) (see Table 5).
- If (i, j) entry in SSIM is A, then (i, j) entry in the reachability matrix will be 0 (for instance, cell 1-3), and the (j, i) entry will be 1 (for instance, cell 3-1).
- If (i, j) entry in SSIM is X, then both the (i, j) and (j, i) value will be 1 in reachability matrix (for instance, cell 3-5 & cell 5-3).
- If (i, j) entry in SSIM is O, then both the (i, j) and (j, i) value will be 0 in reachability matrix (for instance, cell 1-2 & cell 2-1).

5.3 Final reachability matrix

After developing the initial reachability matrix, the driving power and dependency power of each of the factor were assessed. The driving power of a factor was calculated by adding all 1 in the row of that factor and the dependency power of that factor was calculated by adding all 1 in the column of that factor. Table 6 displays the dependency and driving power of each of the identified factors with their ranking. As an example, driving and dependency power of factor 1 (component dependency) is 8 and 12 respectively as seen in Table 5. The driving power of a factor determines how much it influences other factors, whereas, dependency power of a factor determines how much it depends on other factors.

One of the important assumptions in using an ISM is the internal consistency between the factors and their assigned relationships. Therefore, once the initial reachability matrix is developed, for the internal consistency is checked based on the concept of transitivity. Table 6 shows the final reachability matrix after checking internal consistency. Symbol 1* in Table 6 represents the change in the relationship between drivers due to transitivity. From Table 6, it is observed that factor 3 (F3) and factor 9 (F9) has the highest driving power. On the other hand, factor 18 (F18) has the highest dependency.

Table 5. Initial reachability matrix

Factors affecting Product Modularity	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
F1- Component dependency	1	0	1	0	1	0	0	0	1	0	0	1	1	0	1	0	0	1
F2 - Standard component	0	1	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0
F3 - Management decision	1	1	1	0	0	1	1	0	1	0	1	0	0	1	1	1	1	1
F4 - Customization level	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0
F5 - Manufacturability	1	0	1	0	0	1	0	0	0	0	0	1	1	1	1	1	1	0
F6 - Assemble ability	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
F7 - Component lead time	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
F8 - Component availability	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0

Table 5. Continued...

Factors affecting Product Modularity	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
F9 - Product design knowledge	1	1	1	0	1	0	1	0	0	1	0	1	1	1	1	0	1	1
F10 - Inventory management	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0
F11 - Information exchange	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0
F12 - Market demand	1	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0
F13 - Technology & Tools	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	0	0	0
F14 - Product life cycle	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
F15 - Customer awareness	1	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	0	0
F16 - Component interface	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
F17 - Component commonality	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	0
F18 - Product variety	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0

Table 6. Final reachability matrix

Factors affecting Product Modularity	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Driving Power	Rank
F1 - Component dependency	1	0	1	0	1	0	0	0	1	0	0	1	1	0	1	0	0	1	8	4 th
F2 - Standard component	0	1	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	7	5 th
F3 - Management decision	1	1	1	0	0	1*	1	0	1	0	1	0	0	1	1	1	1	1	12	1 st
F4 - Customization level	1	0	0	1*	0	0	1	0	1	0	0	0	0	0	1	0	0	0	5	7 th
F5 - Manufacturability	1	0	1	0	0	1	0	0	0	0	0	1	1	1	1	1	1	0	9	3 rd
F6 - Assemble ability	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	3	9 th
F7 - Component lead time	0	0	0	0	0	0	0	0	0	0	1*	1	0	0	0	0	0	0	2	10 th
F8 - Component availability	0	0	0	0	1*	0	0	0	1	0	1	1*	0	0	0	0	0	0	4	8 th
F9 - Product design knowledge	1	1	1	0	1	0	1	0	0	1	0	1	1	1	1	0	1	1	12	1 st
F10 - Inventory management	0	0	0	0	1*	0	0	0	1	0	1	0	0	0	0	0	0	0	3	9 th
F11 - Information exchange	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	7	5 th
F12 - Market demand	1	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	5	7 th
F13 - Technology & Tools	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	0	0	0	10	2 nd
F14 - Product life cycle	0	0	0	0	1	0	0	0	1*	0	0	0	0	0	0	0	0	0	2	10 th

Table 6. Continued...

Factors affecting Product Modularity	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Driving Power	Rank
	F15 - Customer awareness	1	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	0	0	6
F16 - Component interface	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	4	8 th
F17 - Component commonality	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	0	6	6 th
F18 - Product variety	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0	5	7 th
Dependency Power	12	6	8	3	7	3	6	2	9	1	10	9	7	4	11	2	6	4		
Rank	1 st	7 th	5 th	9 th	6 th	9 th	7 th	10 ^t _h	4 th	11 ^t _h	3 rd	4 th	6 th	8 th	2 nd	10 ^t _h	7 th	8 th		

5.4 Level's partitioning

Level partitioning of modularity factors is done with the objective to determine the importance level of each identified factor. In order to get this importance level for each factor, it is necessary to derive reachability set, antecedent set and intersection set from the final reachability matrix as outlined in Table 6. The resultant level partitioning table is presented in Table 7. The explanation of the data for each set as displayed in Table 7 can be explained as follow:

- Reachability set: It includes the factor itself and the factors it assists to gain.
- Antecedent set: It includes the factor itself and the factors that help it to achieve it.
- Intersection set: It includes the factors that are common in the reachability set and antecedent set.

The level of each factor is determined by checking the factors in the intersection set with the factors in the reachability set. The factors that have the same reachability and intersection sets in the first iteration secure the top level in the hierarchy i.e., level I. In other words, factors which show the minimum variance between reachability set and intersection set secured the highest level, known as level I (Vinod et al., 2019). For instance, in the first iteration, it is noticed that the factors within the reachability set and interaction set of factors 7, 8, 10, 14 are same, which determines them as level I. After identifying the level I factors, all these factors are then removed in the remaining reachability sets and intersection sets. Thereafter, the same procedure is repeated to find the level II factors in the next iteration and continue doing so until the last factor remains in the sets.

The level partitioning or identification process helps in building the digraph and the final ISM model (Singh and Kant, 2008). Table 7 displays the reachability set, antecedent set, intersection set, and final levels of all the factors. The level evaluation process of all the 18 factors is completed in six iterations. In this study maximum level 'VI' was found for factor 9 (Product design knowledge). The top level (level 1) factors are those factors that are driven by others but won't drive others. The factors at the bottom levels represent more dominance, while the factors at the top levels represent less dominance (Moberg et al., 2002).

Table 7. Level partitioning

Factors	Reachability set	Antecedent set	Interaction set	Level
F1	1,4, 6,7,10,14,16,18	1,3,9,16	1,16	IV
F2	2,4,6,8,10,16,17	2,3,5,9,11, 17	2,17	IV
F3	1,2,3,4,5,8,10,12,13,16,17,18	3,5	3,5	V
F4	4, 10,12,15,18	1,2,3,4,5,6, 9,12,13,15,18	4,12,15,18	II
F5	2,3,4,5,6,7,13,16,18	3,4,5,9,13	3,4,5,13	V

Table 7. Continued...

Factors	Reachability set	Antecedent set	Interaction set	Level
F6	4,6,18	1,2,4,5,6,9,11,13,16,17	4,6	III
F7	7,8	1,5,7,8,9,11,13,16,17	7,8	I
F8	7,8,10	2,3,7,8,10,12,13, 15	7,8,10	I
F9	1,2,4,5,6,7,9,12,14,16,17,18	9	9	VI
F10	8,10,14	1,2,3,4,8,10,12,14,17,18	8,10,14	I
F11	2,6,7,11,16,17,18	11	11	V
F12	4,8,10,12,18	3,4,9,12,15,18	4,12,18	II
F13	4,5,6,7,8,13,14,16,17,18	3,5,13	5,13	V
F14	10,14	1,9,10,13,14,15	10,14	I
F15	4,8,12,14,15,18	4,15,18	4,15,18	II
F16	1,6,7,16	1,2,3,5,9,11,13,16	1,16	IV
F17	2,6,7,10,17,18	2,3,9,11,13,17	2,17	IV
F18	4,10,12,15,18	1,3,4,5,6,9,11,12,13,15,17,18	4,12,15,18	II

5.5 Formation of the ISM model

From the level partitioning table, a structural model is developed as shown in Figure 2. For visualizing the directed link between the factors, an arrow is displayed from factor *i* to factor *j*, and the generated diagram is called as the digraph or ISM diagram. Such diagram represents the prominent relationships. The ISM diagram in the figure is developed after removing the transitivity links.

It is obvious from Figure 2 that factor 9 (product design knowledge) will be at the bottom of the ISM model as it has the highest driving power and lowest dependency power. The factors 7, 8, 10, 14 are set at the top of the model as they possess a minimum driving power.

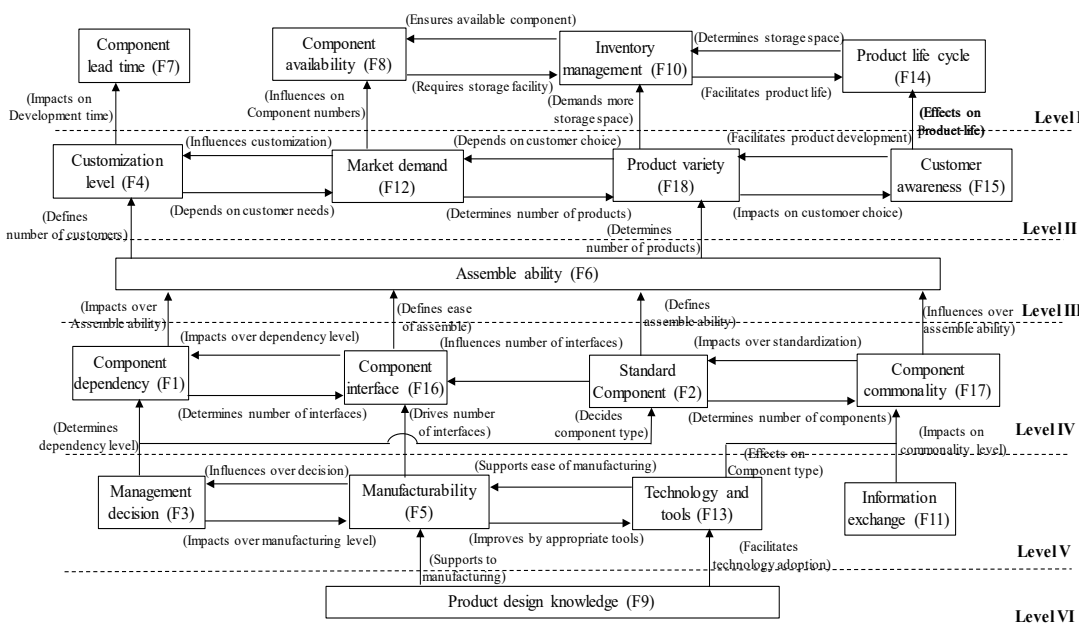


Figure 2. Digraph representation of the prominent relationship in ISM model

From Figure 2, it is noticed that most of the factors from level IV to level VI are strategic in nature. Factors at level IV are mainly related to component interfaces and types, whereas, factors in Level V are associated with organizational strategy. Factor in Level VI is the basis of adopting the modular product development strategy, as the company cannot adopt modular

architecture without having product design knowledge. The top levels of the digraph (Level I, Level II and Level III) consisted of the factors that are mainly associated with operational or tactical issues. To manage these factors, planning or action is needed at mid or lower levels of the management hierarchy. All the factors at Level I, Level II and Level III are related to the dynamic business strategic domain.

In the figure, a short description between each of the links of the identified factors are provided. The objective of such description is to explain briefly how this dependency or interactions impacts or influences one factor on others. This helps industrial manager or product designer to understand cause of linkage between the factors. For instance, factor 'product design knowledge (F9)' facilitates factor 'technology and tools (F13)' through technology adoption. This factor also supports to improve factor 'manufacturability (F5)'. The relationships between the factor 'manufacturability (F5) and factor 'technology and tools (F13)' are in both ways as seen in Figure 2. This two-way relationship indicates that manufacturability improves through appropriate tools, while technology and tools support to ease of manufacturing process. Similar relationships and dependencies between factors are highlighted in Figure 2.

5.6 MICMAC analysis

MICMAC analysis is carried out to scrutinize the impact of driving power and dependency power of the factors (Ansari et al., 2013). Putting the driving power along X-axis and dependency power along Y axis, the factors are divided into four classes namely, autonomous quadrant, dependent quadrant, linkage quadrant and driver quadrant as shown in Figure 3. Each of the quadrants can be explained as follows.

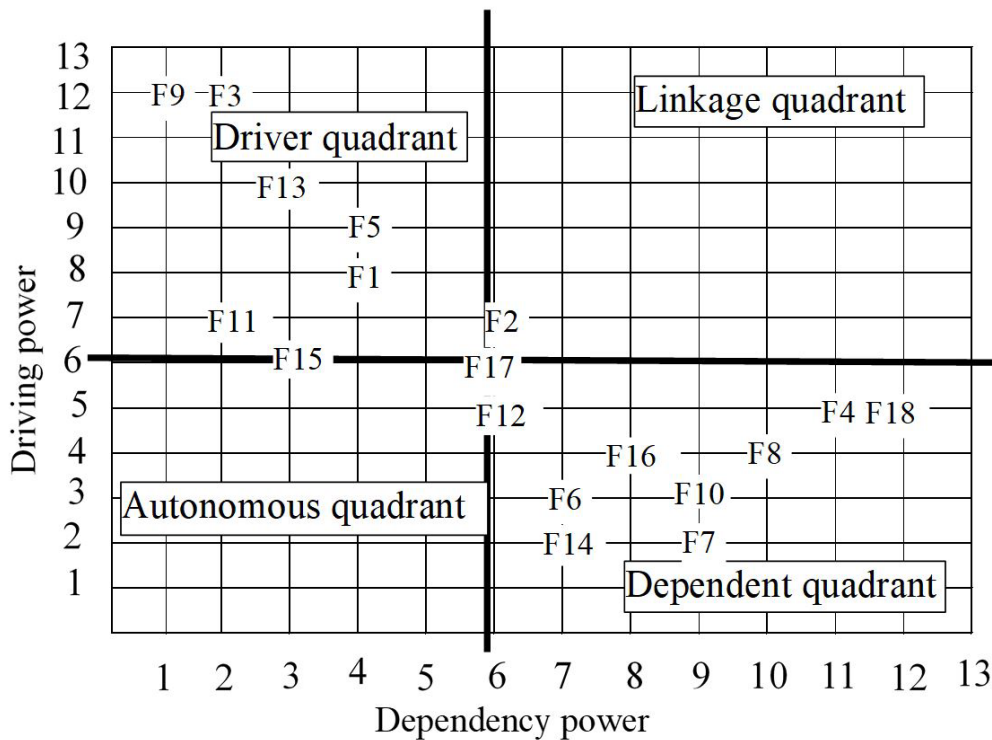


Figure 3. MICMAC analysis based on driving and dependency power

Autonomous quadrant: The factors fall at this quadrant have less driving and dependency power and usually termed as autonomous factors. These drivers are generally disconnected from the system i.e., neither can they strongly drive other drivers nor will

they be strongly driven by others. Figure 3 shows that factors 12, 15 and 17 narrowly lie in this quadrant.

Dependent quadrant: Factors that fall under this quadrant have low driving power but high dependency. From the present study, it is identified that seven factors (F6, F7, F8, F10, F14, F16 and F18) fall under this quadrant. These drivers are strongly affected by the drivers that fall under linkage quadrant.

Linkage quadrant: These are the drivers with high driving power, as well as, high dependency power. They are presented in the third quadrant. They are very important factors as any change in any of these factors has an influence on others. In this study, only one factor (F2) narrowly fall under this quadrant, but also lie very close to the boundary of driver quadrant.

Driver quadrant: This quadrant consists of the factors that has highest driving power but weak dependency. In this study, six factors (F1, F3, F5, F9, F11, and F13) fall under this category. The driver in this quadrant leads to the driver in the other quadrants.

6. PRACTICAL IMPORTANCE

Producing product through piece by piece or module by module is now the ultimate target for all the industries globally to offer true customization with product variety and to survive in today's competitive business world. Customers are now much more aware of their products and they want an increasing amount of customized products. Due to global borderless market, customers have the opportunity to make a choice of products after a huge comparison thus making the market very competitive. To fulfill such customization trend, industries are aiming to produce a customized product for a specific target group and deliver the product to its customers as fast as possible.

It is, however, quite expensive to produce a customized product if the product is monolithic. The customization trend leads the industries to move towards modular product development strategy. In this study, 18 crucial factors were detected for implementing the product modularity strategy. After analyzing the identified factors, it is found that factors 7 (component lead time), 8 (component availability), 10 (inventory management) and 14 (product life cycle) possess the top place (Figure 2), as they have the least driving power and the high dependency power. It indicates that these factors require a low level of consideration to implement the product modularity strategy.

From Figure 2, it is noticed that factor 9 (product design knowledge) is the most prominent factor and it possess the bottom level and has the highest driving power. It is also obvious that factor 9 is driving all the other factors and it can affect other factors acutely. Any change in it will reflect on all other factors. So it should be given the most priority while considering product modularity. Other factors like as F3, F5, F11, and F13 should be given importance just after factor 9. The rest of the factors can be given moderate importance according to their levels. The importance level can be declined gradually from the bottom level to the top level. This is the way to prioritize one factor over another to apply modular product development strategy successfully.

7. DISCUSSIONS AND CONCLUSIONS

This research study mainly deals with to identify the factors that hinder the application to design and develop a modular product. It shows the way out from detecting the obstacles to developing a modular product. In this study, 18 factors were identified which are seen as the obstacles to implementing modular product development strategy. The factors or obstacles are analyzed based on their interrelationships with each other and depicted by creating an ISM model. From this analysis, managers and product designers can get an overall scenario of their product development strategies, especially to design and develop a modular product. Product designers and organizational managers are able to identify the factors that affect decision making process to develop modular product modularity. In addition, such

approach helps them to take necessary actions and allocate resources optimally to implement a modular product development strategy.

The contribution of this paper is to identify the factors associated with developing a modular product. The collected factors were categorized and presented in such a way to the product designers/product planners to offer better visibility about their target products. Such visibility provides the opportunity to the managers to find out the interdependencies among the identified factors, which are ranked by the ISM tool. This tool also provides the relational matrix of the identified factors that helps the product designers and organizational managers to take necessary actions to eliminating potential bottlenecks/barriers to develop modular products. The results from this research study encompass product designers and organizational managers for handling multiple design views, controlling design related interfaces and ranking the status and progress of product modularity and design completeness.

Furthermore, this research helps organizational managers and product designers to investigate the bottlenecks of their product development processes and identify the responsible factors. The factor analysis process contributes towards taking actions against the product development bottlenecks. It saves companies from unexpected losses caused by adopting the wrong strategic decisions during the product development process. From this factor analysis procedure, several critical factors are found out based on their dependencies and driving powers on each other. From the study outcomes, it is noticed that product design knowledge is critical in addition to a management decision, manufacturability, technology and tools and information exchange to adopt modular product development strategy. On the other hand, it is also noticed from the study outcomes that some other factors such as component lead time, component availability, market demand, product variety, customer awareness, etc., have less driving power but higher dependency power to decide for modular product.

Modularity in fact depends on the design to a large extent. The design decision alone can simplify the whole processing system. The top management of each industry should have a big role in the decision making process. Every decision related to product development should be approved by the top management before applying it. The top management is responsible to the entrepreneur for every situation of the business. So before implementing any kind of new decision, it is obvious for them to get the process and the factors that are affecting the process very clearly. The ISM tool as used within this study offers to solve any complex situations in the industry easily through identifying the crucial factors that creates such complexity. This tool supports the top management to get the whole picture or situation of an industry at a glance. Even this tool helps the top management to get a clear idea about the factors hindering the implementation of the new idea. The management team can then take proper steps to eradicate the hindrances. From the developed ISM model, the top management can prioritize the identified critical factors and allocate the necessary efforts and resources accordingly.

Factor identification and analysis is drawing huge attention for the decision making process. The ISM approach can be used for any kind of decision making process before applying it. If the ISM model is applied before applying any decision, the decision will come out more successfully. Moreover, the ISM model can be used for continuous development process too. This model traces out all the new hindrances and analyzes in the same manner to suggest the any new model depends on such kinds of factors analysis. This study does not consider the light factors in consideration with the objective to avoid unwanted intricacy and the possibility of the result to be misconstrued. Someone may find more or fewer factors based on the case to be studied. But, the identified factors in this study are the most common factors for any industry in case of the modular product development process.

In the future study, the results from this study will be tested in various industrial sectors to validate the identified factors to implement modular product development strategy. This approach can be used in other business sectors rather than only product modularity such as modular organizational design, modular process design, modular assembly and layout design,

etc. It can be noted that there may arise new factors responsible for product modularity if the same approach is applied to other business sectors. In the new study, some of the identified factors can be eradicated, while other new factors might be added based on different case studies. In such situations, the ISM study should be repeatedly performed in order to improve the overall processes.

REFERENCES

- Agrawal, P., Narain, R. and Ullah, I. (2019), "Analysis of barriers in implementation of digital transformation of supply chain using interpretive structural modelling approach", *Journal of Modelling in Management*, Vol. 15, No. 1, pp. 297-317. <http://dx.doi.org/10.1108/JM2-03-2019-0066>.
- Ansari, M.F., Kharb, R.K., Luthra, S. et al. (2013), "Analysis of barriers to implement solar power installations in India using interpretive structural modeling technique", *Renewable & Sustainable Energy Reviews*, Vol. 27, pp. 163-74. <http://dx.doi.org/10.1016/j.rser.2013.07.002>.
- Asadi, N., Jackson, M. and Fundin, A. (2019), "Implications of realizing mix flexibility in assembly systems for product modularity—A case study", *Journal of Manufacturing Systems*, Vol. 52, pp. 13-22. <http://dx.doi.org/10.1016/j.jmsy.2019.04.010>.
- Attri, R., Dev, N. and Sharma, V. (2013), "Interpretive Structural Modelling (ISM) approach: an overview", *Research Journal of Management Sciences*, Vol. 2, No. 2, pp. 3-8.
- Baldwin, C.Y. and Clark, K.B. (2000), *Design Rules: The Power of Modularity*, Vol. 1, MIT Press, USA. <http://dx.doi.org/10.7551/mitpress/2366.001.0001>.
- Barbosa, L.M., Lacerda, D.P., Piran, F.A.S. et al. (2017), "Exploratory analysis of the variables prevailing on the effects of product modularization on production volume and efficiency", *International Journal of Production Economics*, Vol. 193, pp. 677-90. <http://dx.doi.org/10.1016/j.ijpe.2017.08.028>.
- Baylis, K., Zhang, G. and McAdams, D.A. (2018), "Product family platform selection using a Pareto front of maximum commonality and strategic modularity", *Research in Engineering Design*, Vol. 29, No. 4, pp. 547-63. <http://dx.doi.org/10.1007/s00163-018-0288-5>.
- Ben-Daya, M. and Raouf, A. (1994), "Inventory models involving lead time as a decision variable", *The Journal of the Operational Research Society*, Vol. 45, No. 5, pp. 579-82. <http://dx.doi.org/10.1057/jors.1994.85>.
- Breidert, J. and Welp, E.G. (2003), "Tools supporting the development of modular systems", in *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design*, Stockholm, pp. 341-342.
- Bruun, H.P.L., Mortensen, N.H., Harlou, U. et al. (2015), "PLM system support for modular product development", *Computers in Industry*, Vol. 67, pp. 97-111. <http://dx.doi.org/10.1016/j.compind.2014.10.010>.
- Buergin, J., Belkadi, F., Hupays, C. et al. (2018), "A modular-based approach for Just-In-Time Specification of customer orders in the aircraft manufacturing industry", *CIRP Journal of Manufacturing Science and Technology*, Vol. 21, pp. 61-74. <http://dx.doi.org/10.1016/j.cirpj.2018.01.003>.
- Cebon, P., Hauptman, O. and Shekhar, C. (2008), "Product modularity and the product life cycle: new dynamics in the interactions of product and process technologies", *International Journal of Technology Management*, Vol. 42, No. 4, pp. 365-86. <http://dx.doi.org/10.1504/IJTM.2008.019381>.
- Chakravarty, A.K. and Balakrishnan, N. (2001), "Achieving product variety through optimal choice of module variations", *IIE Transactions*, Vol. 33, No. 7, pp. 587-98. <http://dx.doi.org/10.1080/07408170108936856>.
- Clemente, D., Hsuan, J. and Carvalho, M. (2019), "The intersection between business model and modularity: an overview of the literature", *Brazilian Journal of Operations & Production Management*, Vol. 16, No. 3, pp. 387-97. <http://dx.doi.org/10.14488/BJOPM.2019.v16.n3.a3>.
- Collier, D.A. (1981), "The measurement and operating benefits of component part commonality", *Decision Sciences*, Vol. 12, No. 1, pp. 85-96. <http://dx.doi.org/10.1111/j.1540-5915.1981.tb00063.x>.
- Colombo, E.F., Shougarian, N., Sinha, K. et al. (2020), "Value analysis for customizable modular product platforms: theory and case study", *Research in Engineering Design*, Vol. 31, No. 1, pp. 123-40. <http://dx.doi.org/10.1007/s00163-019-00326-4>.
- Efatmaneshnik, M., Shoal, S. and Qiao, L. (2020), "A standard description of the terms module and modularity for systems engineering", *IEEE Transactions on Engineering Management*, Vol. 67, No. 2, pp. 365. <http://dx.doi.org/10.1109/TEM.2018.2878589>.

- ElMaraghy, H. and AlGeddawy, T. (2012), "New dependency model and biological analogy for integrating product design for variety with market requirements", *Journal of Engineering Design*, Vol. 23, No. 10-11, pp. 722-45. <http://dx.doi.org/10.1080/09544828.2012.709607>.
- Erixon, G., Von Yxkull, A. and Arnström, A. (1996), "Modularity: the basis for product and factory reengineering", *CIRP Annals*, Vol. 45, No. 1, pp. 1-6. [http://dx.doi.org/10.1016/S0007-8506\(07\)63005-4](http://dx.doi.org/10.1016/S0007-8506(07)63005-4).
- Erixon, G., Erlandsson, A., Von Yxkull, A. et al. (1994), *Modulindela Produkten*, Industrilitteratur, Stockholm.
- Esterman, M., Palekar, S., Conway, F. et al. (2020), "Toward robust concurrent product development across the supply chain: a risk assessment framework", *Journal of Engineering Design*, Vol. 31, No. 3, pp. 150-77. <http://dx.doi.org/10.1080/09544828.2019.1685659>.
- Eswarlal, V.K., Kumar Dey, P. and Shankar, R. (2011), "Enhanced renewable energy adoption for sustainable development in India: Interpretive structural modeling approach", in *World Renewable Energy Congress*, Linköping University, Linköping, Sweden. <http://dx.doi.org/10.3384/ecp11057351>.
- Gershenson, J.K. and Prasad, G.J. (1997), "Modularity in product design for manufacturability", *International Journal of Agile Manufacturing*, Vol. 1, No. 1, pp. 99-110.
- Hackl, J., Krause, D., Otto, K. et al. (2020), "Impact of modularity decisions on a firm's economic objectives", *Journal of Mechanical Design*, Vol. 142, No. 4, pp. 11. <http://dx.doi.org/10.1115/1.4044914>.
- Hernández, K.E., Olivares-Benítez, E. and Zuñiga, C.A. (2015), "Safety stock levels in modular product system using commonality and part families", *IFAC-PapersOnLine*, Vol. 48, No. 3, pp. 1387-92. <http://dx.doi.org/10.1016/j.ifacol.2015.06.280>.
- Jose, A. and Tollenaere, M. (2005), "Modular and platform methods for product family design: literature analysis", *Journal of Intelligent Manufacturing*, Vol. 16, No. 3, pp. 371-90. <http://dx.doi.org/10.1007/s10845-005-7030-7>.
- Kamali, M. and Hewage, K. (2016), "Life cycle performance of modular buildings: a critical review", *Renewable & Sustainable Energy Reviews*, Vol. 62, pp. 1171-83. <http://dx.doi.org/10.1016/j.rser.2016.05.031>.
- Kim, D.-Y., Park, J.-W., Baek, S. et al. (2020), "A modular factory testbed for the rapid reconfiguration of manufacturing systems", *Journal of Intelligent Manufacturing*, Vol. 31, No. 3, pp. 661-80. <http://dx.doi.org/10.1007/s10845-019-01471-2>.
- Lau, A.K., Yam, R.C. and Tang, E. (2011), "The impact of product modularity on new product performance: Mediation by product innovativeness", *Journal of Product Innovation Management*, Vol. 28, No. 2, pp. 270-84. <http://dx.doi.org/10.1111/j.1540-5885.2011.00796.x>.
- Lau, A.K., Yam, R.C. and Tang, E.P. (2010), "Supply chain integration and product modularity: An empirical study of product performance for selected Hong Kong manufacturing industries", *International Journal of Operations & Production Management*, Vol. 30, No. 1, pp. 20-56. <http://dx.doi.org/10.1108/01443571011012361>.
- Loureiro, G.B., Ferreira, J.C.E. and Messerschmidt, P.H.Z. (2020), "Design structure network (DSN): a method to make explicit the product design specification process for mass customization", *Research in Engineering Design*, Vol. 31, No. 2, pp. 197-220. <http://dx.doi.org/10.1007/s00163-020-00331-y>.
- Malek, J. and Desai, T.N. (2019), "Interpretive structural modelling based analysis of sustainable manufacturing enablers", *Journal of Cleaner Production*, Vol. 238, No. 20, pp. 117996. <http://dx.doi.org/10.1016/j.jclepro.2019.117996>.
- Mandal, A. and Deshmukh, S.G. (1994), "Vendor selection using interpretive structural modelling (ISM)", *International Journal of Operations & Production Management*, Vol. 14, No. 6, pp. 52-9. <http://dx.doi.org/10.1108/01443579410062086>.
- Marion, T.J., Meyer, M.H. and Barczak, G. (2015), "The influence of digital design and it on modular product architecture", *Journal of Product Innovation Management*, Vol. 32, No. 1, pp. 98-110. <http://dx.doi.org/10.1111/jpim.12240>.
- Marshall, R. and Leaney, P.G. (1999), "A systems engineering approach to product modularity", *Proceedings of the Institution of Mechanical Engineers. Part B, Journal of Engineering Manufacture*, Vol. 213, No. 8, pp. 847-51. <http://dx.doi.org/10.1243/0954405991517272>.
- Meissner, D., Burton, N., Galvin, P. et al. (2020), "Understanding cross border innovation activities: The linkages between innovation modes, product architecture and firm boundaries", *Journal of Business Research*, in press. <http://dx.doi.org/10.1016/j.jbusres.2019.05.025>.
- Mesa, J.A., Esparragoza, I. and Maury, H. (2020), "Modular Architecture Principles – MAPs: a key factor in the development of sustainable open architecture products", *International Journal of Sustainable Engineering*, Vol. 13, No. 2, pp. 108-22. <http://dx.doi.org/10.1080/19397038.2019.1634157>.

- Moberg, C.R., Cutler, B.D., Gross, A. et al. (2002), "Identifying antecedents of information exchange within supply chains", *International Journal of Physical Distribution & Logistics Management*, Vol. 32, No. 9, pp. 755-70. <http://dx.doi.org/10.1108/09600030210452431>.
- Mondragon, A.E.C. and Mondragon, C.E.C. (2018), "Managing complex, modular products: how technological uncertainty affects the role of systems integrators in the automotive supply chain", *International Journal of Production Research*, Vol. 58, No. 20, pp. 6628-43. <http://dx.doi.org/10.1080/00207543.2018.1424362>.
- Pahl, G. and Beitz, W. (2013), *Engineering Design: a Systematic Approach*, Springer Science & Business Media, London.
- Pashaei, S. and Olhager, J. (2015), "Product architecture and supply chain design: a systematic review and research agenda", *Supply Chain Management*, Vol. 20, No. 1, pp. 98-112. <http://dx.doi.org/10.1108/SCM-12-2013-0487>.
- Peng, G. and Mu, J. (2018), "Do modular products lead to modular organisations? Evidence from open source software development", *International Journal of Production Research*, Vol. 56, No. 20, pp. 6719-33. <http://dx.doi.org/10.1080/00207543.2018.1492753>.
- Piya, S., Khadem, M. and Shamsuzzoha, A. (2016), "Negotiation based decision support system for order acceptance", *Journal of Manufacturing Technology Management*, Vol. 27, No. 3, pp. 443-68. <http://dx.doi.org/10.1108/JMTM-04-2015-0023>.
- Piya, S., Shamsuzzoha, A., Khadem, M. et al. (2017), "Supply chain complexity drivers and solution methods", *International Journal of Supply Chain Management*, Vol. 6, No. 4, pp. 43-50.
- Piya, S., Shamsuzzoha, A. and Khadem, M. (2020a), "An approach for analysing supply chain complexity drivers through interpretive structural modelling", *International Journal of Logistics Research and Applications*, Vol. 23, No. 4, pp. 311-36. <http://dx.doi.org/10.1080/13675567.2019.1691514>.
- Piya, S., Shamsuzzoha, A., Khadem, M. et al. (2020b), "Measuring supply chain complexity based on multi-criteria decision approach", in *Proceedings of the 10th International Conference on Industrial Engineering and Operations Management*, UAE, Dubai.
- Rajagopal, G. and Ramasamy, R. (2020), "Modelling the drilling crew induced process disruption factors using an ISM – MICMAC approach", *International Journal of Services and Operations Management*, Vol. 35, No. 1, pp. 115. <http://dx.doi.org/10.1504/IJSOM.2020.104335>.
- Rennpferdt, C., Greve, E. and Krause, D. (2019), "The impact of modular product architectures in pss design: a systematic literature review", *Procedia CIRP*, Vol. 84, pp. 290-5. <http://dx.doi.org/10.1016/j.procir.2019.04.197>.
- Salvador, F., Forza, C. and Rungtusanatham, M. (2002), "Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, Vol. 20, No. 5, pp. 549-75. [http://dx.doi.org/10.1016/S0272-6963\(02\)00027-X](http://dx.doi.org/10.1016/S0272-6963(02)00027-X).
- Servaes, H. and Tamayo, A. (2013), "The impact of corporate social responsibility on firm value: the role of customer awareness", *Management Science*, Vol. 59, No. 5, pp. 1045-61. <http://dx.doi.org/10.1287/mnsc.1120.1630>.
- Shaik, A.M., Rao, V.V.S.K. and Rao, C.S. (2015), "Development of modular manufacturing systems: a review", *International Journal of Advanced Manufacturing Technology*, Vol. 76, No. 5-8, pp. 789-802. <http://dx.doi.org/10.1007/s00170-014-6289-2>.
- Shamsuzzoha, A. and Helo, P. (2017), "Development of sustainable platform for modular product family: a case study", *Production Planning and Control*, Vol. 28, No. 6-8, pp. 512-23. <http://dx.doi.org/10.1080/09537287.2017.1309715>.
- Shamsuzzoha, A., Helo, P., Piya, S. et al. (2020), "Modular product architecture to manage product development complexity", *International Journal of Industrial and Systems Engineering*, in press.
- Shamsuzzoha, A., Piya, S., Al-Kindi, M. et al. (2018), "Metrics of product modularity: lessons learned from case companies", *Journal of Modelling in Management*, Vol. 13, No. 2, pp. 331-50. <http://dx.doi.org/10.1108/JM2-12-2016-0127>.
- Shoval, S. and Efatmaneshnik, M. (2019), "Managing complexity of assembly with modularity: a cost and benefit analysis", *International Journal of Advanced Manufacturing Technology*, Vol. 105, No. 9, pp. 3815-28. <http://dx.doi.org/10.1007/s00170-019-03802-2>.
- Silveira, G.D., Borenstein, D. and Fogliatto, F.S. (2001), "Mass customization: literature review and research directions", *International Journal of Production Economics*, Vol. 72, No. 1, pp. 1-13. [http://dx.doi.org/10.1016/S0925-5273\(00\)00079-7](http://dx.doi.org/10.1016/S0925-5273(00)00079-7).

- Singh, M.D. and Kant, R. (2008), "Knowledge management barriers: an interpretive structural modeling approach", *International Journal of Management Science and Engineering Management*, Vol. 3, No. 2, pp. 141-50. <http://dx.doi.org/10.1080/17509653.2008.10671042>.
- Singh, M.D., Shankar, R., Narain, R. et al. (2003), "An interpretive structural modeling of knowledge management in engineering industries", *Journal of Advances in Management Research*, Vol. 1, No. 1, pp. 28-40. <http://dx.doi.org/10.1108/97279810380000356>.
- Sosa, M.E., Eppinger, S.D. and Rowles, C.M. (2004), "The Misalignment of Product Architecture and Organizational Structure in Complex Product Development", *Management Science*, Vol. 50, No. 12, pp. 1615-1761. <http://dx.doi.org/10.1287/mnsc.1040.0289>.
- Sun, H. and Lau, A. (2019), "The impact of modular design and innovation on new product performance: The role of product newness", *Journal of Manufacturing Technology Management*, Vol. 31, No. 2, pp. 370-91. <http://dx.doi.org/10.1108/JMTM-09-2018-0319>.
- Tu, Q., Vonderembse, M.A., Ragu-Nathan, T.S. et al. (2004), "Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective", *Decision Sciences*, Vol. 35, No. 2, pp. 147-68. <http://dx.doi.org/10.1111/j.00117315.2004.02663.x>.
- Ulrich, K. and Tung, K. (1991), "Fundamentals of product modularity", in *Proceedings of the 1991 ASME Design Engineering Technical Conferences—Conference on Design/Manufacture Integration*, Miami, FL.
- Ulrich, K. (1994), "Fundamentals of product modularity", in Dasu, S. and Eastman, C. (Eds.), *Management of Design*, Springer, Netherlands, pp. 219-231. http://dx.doi.org/10.1007/978-94-011-1390-8_12.
- Vinod, N., Kumar, R. and Singh, S.K. (2019), "Barriers identification and analysis of solar power implementation in Indian thermal power plants: An Interpretative Structural Modeling approach", *Renewable & Sustainable Energy Reviews*, Vol. 114, pp. 109330. <http://dx.doi.org/10.1016/j.rser.2019.109330>.
- Watanabe, C. and Ane, B.K. (2004), "Constructing a virtuous cycle of manufacturing agility: concurrent roles of modularity in improving agility and reducing lead time", *Technovation*, Vol. 24, No. 7, pp. 573-83. [http://dx.doi.org/10.1016/S0166-4972\(02\)00118-9](http://dx.doi.org/10.1016/S0166-4972(02)00118-9).
- Wilschut, T., Etman, L.F.P., Rooda, J.E. et al. (2019), "Similarity, modularity, and commonality analysis of navigation Locks in the Netherlands", *Journal of Infrastructure Systems*, Vol. 25, No. 1, pp. 04018043 [http://dx.doi.org/10.1061/\(ASCE\)IS.1943-555X.0000468](http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000468).
- Zhang, M., Guo, H., Huo, B. et al. (2019), "Linking supply chain quality integration with mass customization and product modularity", *International Journal of Production Economics*, Vol. 207, pp. 227-35. <http://dx.doi.org/10.1016/j.ijpe.2017.01.011>.
- Zhang, M., Zhao, X. and Qi, Y. (2014), "The effects of organizational flatness, coordination, and product modularity on mass customization capability", *International Journal of Production Economics*, Vol. 158, pp. 145-55. <http://dx.doi.org/10.1016/j.ijpe.2014.07.032>.

Author contributions: Ahm Shamsuzzoha: Conceptualization, formulation, data collection, methodology, writing, revising. Sujan Piya: Methodology, data analysis, formulation.