Modular Product Development – Mapping and Prioritizing the Driving Factors by Interpretive Structural Modelling

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Abstract

Modular product development strategy facilitates developing new products tailored to emerging markets globally. It has broad implications for product performance, product variety, product change, manufacturability and assemble ability. However, it is not an easy task to adopt such strategy as many drivers affect its implementation. Therefore, before its implementation, it is imperative that manufacturer understand the driving factors of modular product design. This research identifies 18 driving factors, which are necessary to boost up modular product design and development. These factors are identified and sorted out through extensive literature surveys and experts opinions from industrial personnel and academicians. Thereafter, the interdependencies among the factors are classified as high, medium and low through the use of Interpretive Structural Modeling (ISM). The ISM diagraph shows that modularity factors can be classified into six levels. Factor “Product development knowledge” falls at the lowest level of ISM diagraph indicating that it has the highest driving power for modular product development strategy. On the other hand, factors such as “Component lead time”, “Component availability”, “Inventory management” and “Product life cycle” are the factors with highest dependency.

Keywords
Product modularity, modularity factors, ISM, mass customization, expert opinions

1. Introduction

Global manufacturing industries are undergoing a major shift from traditional manufacturing process to flexible manufacturing. This flexibility offers manufacturing companies to rapidly responding to all changes in the global market environment through rationalizing its manufacturing facilities and producing a large variety of products at lower cost in time. However, it is not an easy task to develop product variety with limited resources. In order to stay competitive in today’s market segment, it is crucial to develop product variety due to increased level of customization. Global customers are more selective than ever, which creates extra pressure on manufacturing companies to develop variety of products with limited resources. In such circumstances, modular product development and reconfigurable processes strategy provide a way to produce a variety of products to satisfy mass customers. This modular product design and development strategy provides crucial agile manufacturing through the combination of distinct building blocks (modules). This strategy is becoming a focus of attention in current manufacturing processes.

Modular product design and development process refers to a product whose components fulfill various functions through the combination of distinct building blocks or modules composed of certain components. 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, manufacturer can generate a potentially large number of different products in a modular product model. Such 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. Therefore, modular product development strategy is an important source of strategic flexibility. However, it is not an easy task to adopt modular product development strategy. Many drivers may affect implementation of this strategy. Therefore, before its implementation, it is imperative that manufacturer understand the drivers of that affect implementation of such strategy.

The purposes of this study can be outlined as:

1. To identify the critical factors or drivers that affect product modularity.
2. To establish inter-relationships among the drivers.
3. To identify the priority level of the factors or drivers.

2. Literature review

Nowadays, product modularity is the buzzword in industrial area. Customers wish to have more customized products with lower costs. Modularity process aims to produce more customized products with lower costs in order to satisfy the customers. It focuses to produce independent, standardized and interchangeable product to get the variety of functionalities. For wide ranges of overall functions, partitioning the modules based on function is important On the other hand,e for a small range of overall function it is wise to partitioning module based on production process. In this regard, Mikkola and Gassmann (2003) assert that for large product variants high modularity is required, whereas, low modularity permits optimization of product component for a specific product.

Functional modules aims at applying technical function individually or in combination with others, while production modules are planned autonomously of their function and based on production process. Functional modules can be divided into four categories of basic, auxiliary, adaptive and non-modules (Huang and w Kusiak, 1998). Baldwin and Clark (1997) said product modularity is the best approach to deal this complexity. Product modularity is a process where common units are used to produce varieties of product. Ulrich (1994) defined modularity in terms of product design based on two categories. First category is based on the similarity between the physical and functional architecture of the design. Next, it is based on the minimization of identical interactions between physical components.

To survive in the competitive business environment the industries are willing to adopt modularity process. But, there are many factors which affect the decision of product modularity. For identifying the factors and the interdependencies among them interpretive structural modeling (ISM) is used. ISM is an interactive learning process in which some unique and straightforwardly related factors are organized into a model (Ansari et al., 2013). The model helps to identify contextual relationships between the factors (Piya et al., 2016). ISM also helps to identify the priority level of factors by developing ISM diagraph (Chidambaranathan et al., 2009; Mandal and Deshmukh, 1994).

3. Factors identifications

Every decision making process goes through consideration of some factors. These factors have direct or indirect impact over the decision. Similarly, in product modularity process there exists a plethora of factors. The factors those affect the product modularity decisions severely are collected based on expertise opinions and from literature review. The factors affecting the product modularity are summarized in Table 1 along with their corresponding references from the literature.

Table 1. Factors affecting product modularity based on literature review

Serial number	Factors affecting the product modularity	References	Serial number	Factors affecting the product modularity	References
1	Component dependency	Gershenson and Prasad, 1997	10	Inventory management	Ben-Daya and Raouf, 1994
2	Standard component	Boothroyd, 1994	11	Information exchange	Moberg et al. 2002
3	Management decision	Singh et al., 2003	12	Market demand	Gershenson and Prasad, 1997
4	Customization level	Silveira et al., 2001	13	Technology & Tools	Ioannis et al. 1999

5	Manufacturability	Boothroyd, 1994; Boothroyd, 1994	14	Product life cycle	Silveira et al., 2001; Ulrich, 1994.
6	Assemble ability	Boothroyd, 1994; Salvador et al., 2002	15	Customer awareness	Servaes and Tamayo, 2013
7	Component lead time	Ulrich, 1994; Gershenson and Prasad, 1997	16	Component interface	Gershenson and Prasad, 1997
8	Component availability	Ulrich, 1994	17	Component commonality	Collier, 1981
9	Product design knowledge	Gerhard and Beitz, 2013	18	Product variety	Ulrich, 1994

4. ISM methodology

After identifying driving factors of modularity, the research analyzes the interdependency of these factors through the use of ISM methodology. This method first asserted by Warfield in 1973, is considered as the most effective method to deal with complex issues (Ansari et al., 2013). The procedural steps for developing an ISM model, are showed in Figure 1 (Mandal and Deshmukh, 1994; Eswarlal et al., 2011).

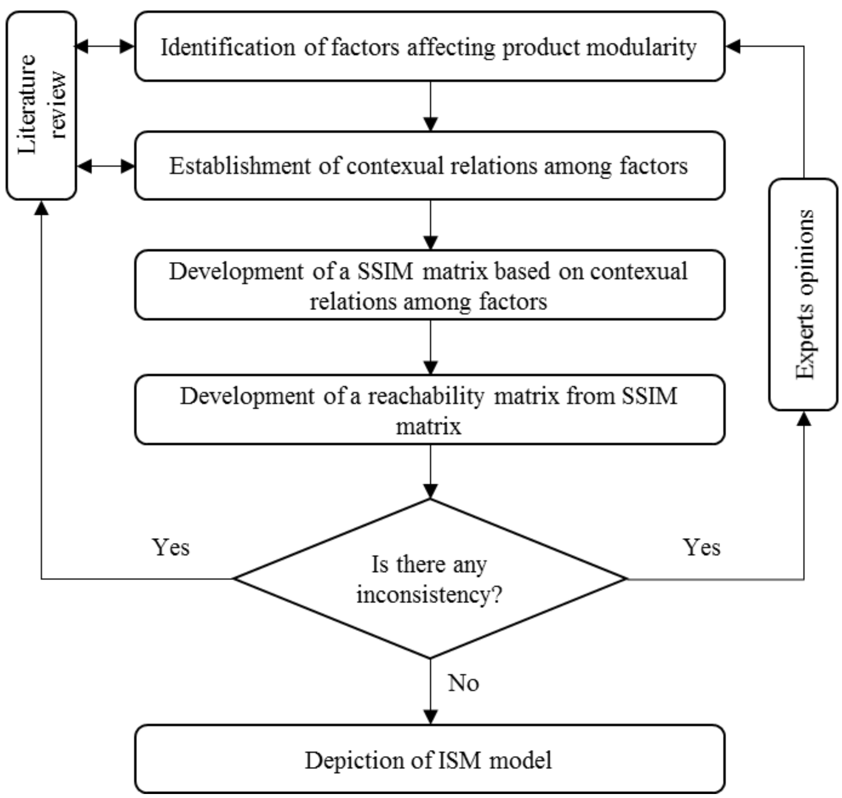

Figure 1. ISM procedural steps

4.1. Factors identification and developing contextual relationship

The factors affecting the implementation of product modularity are identified as shown in Table 1. The identification is based on extensive literature review and experts opinion. A structural self-interaction matrix (SSIM) is used to construct contextual relationship that exists between identified factors. The relationship between one factors with others is identified through experts' opinion. SSIM is developed using V/A/X/O symbol. The explanation of these symbols are given below:

"V" denotes factor 'i' assists gaining factor 'j';
"A" denotes factor 'j' assists gaining factor 'i';
"x" denotes factor 'i' and 'j' assist gaining each other;
"O" denotes factor 'i' and 'j' are not related;

SSIM for the driving factors of modular product development model is as shown in Table 2. Factor 1 will help achieving factor 4, hence "V" sign is used in 1-4 cell (Table 2). Similarly factor 2 needs help from factor 3, hence "A" signed is used in cell 2-3. Factor 3 and 5 will help each other to achieve, hence "X" sign is used in this case. Factor 6 and 7 are unrelated, so "O" sign is used here (6-7 cell). Similarly, all such inter-relationships are analyzed between each pair of factor to come up with SSIM.

Table 2. Structural self-interaction matrix (SSIM)

Factors affecting Product Modularity	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1. Component dependency	V	O	X	O	V	O	O	O	V	A	O	V	V	V	V	A	O	
2. Standard component	V	X	V	A	O	O	A	A	V	A	V	O	V	A	V	A		
3. Management decision	V	V	V	A	O	V	X	O	V	O	V	O	O	X	V			
4. Customization level	X	V	O	A	O	A	X	O	V	A	A	O	X	A				
5. Manufacturability	V	O	V	O	O	X	O	O	O	A	O	V	V					
6. Assemble ability	V	A	A	O	O	A	O	A	O	A	O	O						
7. Component lead time	O	A	A	O	O	A	O	A	O	A	O							
8. Component availability	V	O	O	A	O	A	A	O	X	O								
9. Product design knowledge	V	V	V	O	V	O	V	O	O									
10. Inventory management	A	A	O	O	O	O	A	O										
11. Information exchange	V	V	V	O	O	O	O											
12. Market demand	X	O	O	A	O	O												
13. Technology & Tolls	V	V	V	O	V													
14. Product life cycle	O	O	O	A														
15. Customer awareness	X	O	O															
16. Component interface	O	O																
17. Component commonality	V																	
18. Product variety																		

4.2. Reachability matrix (RM)

The reachability matrix is a binary matrix, which is extracted from SSIM matrix based on the following rules:

- If (i, j) entry in SSIM is V, then (i, j) entry in RM will be 1 (cell 1-4), and the (j, i) entry will be 0 (cell 4-1) (see Table 3).
- If (i, j) entry in SSIM is A, then (i, j) entry in RM will be 0 (cell 1-3), and the (j, i) entry will be 1 (cell 3-1).
- Both the (i, j) and (j, i) value will be 1 in RM if the sign is X for an entry (cell 3-5 & cell 5-3).
- Both the (i, j) and (j, i) value will be 0 in RM if the sign is O for an entry (cell 1-2 & cell 2-1).

After generating RM the driving power and dependency power is computed for each factor. The driving power of a factor is computed by adding all 1's for that factor's row and the dependency power is obtained by adding all 1's from the factor's column.

Table 3. 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
1. Component dependency	1	0	1	0	1	0	0	0	1	0	0	1	1	1	1	0	0	1	9
2. Standard component	1	1	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	8
3. Management decision	1	1	1	0	0	1	1	0	1	0	1	0	0	1	1	1	1	1	12
4. Customization level	1	1	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	6
5. Manufacturability	1	0	1	0	0	1	0	0	0	0	0	1	1	1	1	1	1	0	9
6. Assemble ability	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	3
7. Component lead time	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
8. Component availability	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	4
9. Product design knowledge	1	1	1	0	1	0	1	0	0	1	0	1	1	1	1	0	1	1	12
10. Inventory management	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	2
11. Information exchange	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	7
12. Market demand	1	0	0	0	0	0	1	0	1	0	1	0	0	0	1	1	1	0	7
13. Technology & Tolls	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	0	0	0	10
14. Product life cycle	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
15. Customer awareness	1	0	0	1	1	0	1	0	0	0	1	0	0	0	1	1	1	0	8
16. Component interface	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	4
17. Component commonality	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	0	6
18. Product variety	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0	5

4.3 Level partitioning

This step helps to cluster the identified factors into various levels. To do so the reachability set, antecedent set and the intersection set is derived from the reachability matrix. The explanation of each set is as follow:

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

The factors that have the same reachability and intersection sets in the first iteration will be given level I. It represents minimum variance between reachability set and intersection set (Vasanthakumar et al., 2016). Once the factors in level I are identified they are removed from all remaining reachability set and intersection set. Then, the process is repeated to find the second level factors in the next iteration and so on until the last factor remains in the sets. The outcome of number of iterations is as shown in Table 4. Table shows that factors of modularity product development strategy are clustered into six different levels.

4.4 Developing ISM model

Based on the various levels obtained from step 3 a systematic model known as directed graph or ISM diagraph is generated as shown in Figure 2. The relationship between factors i and j is shown by an arc directed from i to j in the graph. The graph shows that ISM methodology cluster factors of modularity development strategy into six levels. "Product design knowledge" i.e., factor 9 falls at the bottom of the graph representing that it has the highest driving power. Factors 7, 8, 10 and 14 are set at the top of the graph as they possess a minimum driving power. It shows that they depends on all other factors that affect the development of modular product. Other factors lie within these two levels. Therefore, from the analysis it can be concluded that the most important factor is "Product design knowledge" if the company wants to move towards modular product development strategy to become competitive.

Table 4. Level partitioning

Factors	Reachability set	Antecedent set	Interaction set	Level
1	1,4,5,6,7,10,14,16,18	1,3,9,16	1,16	iv
2	2,4,6,8,10,16,17	2,3,5,9,11,12,15,17	2,17	iv
3	1,2,3,4,5,8,10,12,13,16,17,18	3,5,12,15	3,5,12	v
4	4,6,10,12,17,18	1,2,3,4,5,6,8,9,12,13,15,18	4,6,12,18	ii
5	2,3,4,5,6,7,13,16,18	1,3,4,5,9,13	3,4,5,13	v
6	4,6,18	1,2,4,5,6,9,11,13,16,17	4,6	iii
7	7	1,5,7,9,11,13,16,17	7	i
8	4,8,10,18	2,3,8,10,12,13,15	8,10	i
9	1,2,4,5,6,7,9,12,14,16,17,18	9	9	vi
10	8,10	1,2,3,4,8,10,12,17,18	8,10	i
11	2,6,7,11,16,17,18	11	11	v
12	2,3,4,8,10,12,18	3,4,9,12,15,18	3,4,12,18	ii
13	4,5,6,7,8,13,14,16,17,18	3,5,13	5,13	v
14	14	1,9,13,14,15	14	i
15	2,3,4,8,12,14,15,18	15,18	15,18	ii
16	1,6,7,16	1,2,3,5,9,11,13,16	1,16	iv
17	2,6,7,10,17,18	2,3,4,9,11,13,17	2,17	iv
18	4,10,12,15,18	1,2,3,4,5,6,8,9,11,12,13,15,17,18	4,12,15,18	ii

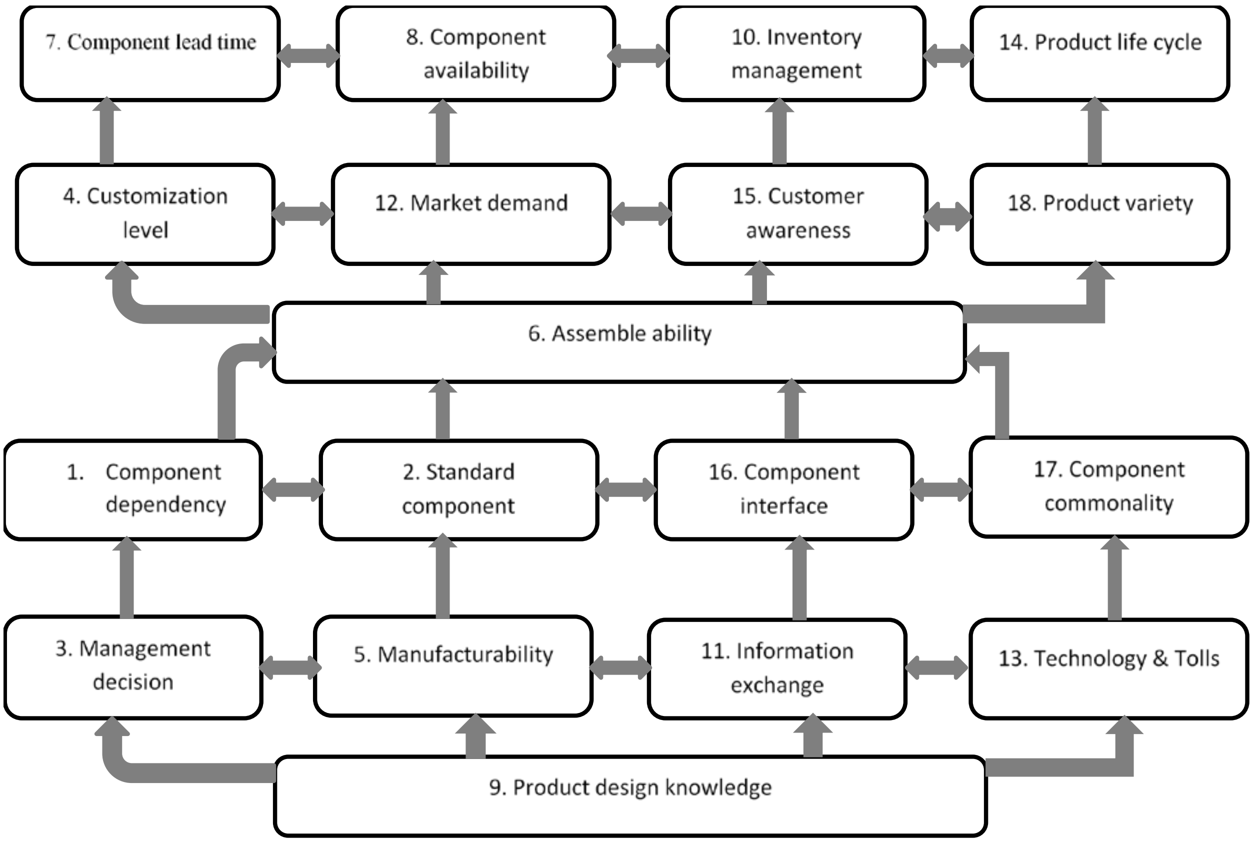

Figure 2: ISM model

5. Conclusions

This paper deals with the factors that hinder the application of product modularity process in industry. In this avenue, 18 factors were identified after literature review and were analyzed with respect to modular product development using ISM. ISM analyzed these factors based on their inter-relationship with each other and the intensity of their impact over the decision on product modularity. Modularity in fact depends on the design to a large extent. It is noticed that product design knowledge (factor 9) has highest impact on the product modularity. The design decision alone can simplify the whole processing system. It has the most driving power. If it is altered, there will be a huge effect on the all other factors.

The other factors like 3 (management decision), 5 (manufacturability), 11(information exchange), and 13(technology & tools) are placed over the factor 9 (product design knowledge). These are also important factors to be emphasized just after factor 9. They can drive the factors over them. Any change in these factors will affect the factors over them. Factor 7 (component lead time), 8 (component availability), 10 (inventory management) and 14 (product life cycle) require the least consideration for applying the decision.

From this analysis, it is also observed that top management can get the overall idea about the hindrances in case of applying any particular decision. They can also get the idea what to do to reduce the impact of such hindrances. We didn't take the light factors in consideration to avoid unwanted intricacy and the possibility of the result to be misconstrued. After the implementation of this study, it may arise new factors while some of the factors here can be eradicated.

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