Application of Product Modularity in Industry: a Case Study

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Abstract

Product modularity is a design strategy that offers mutual benefits to the manufacturing companies. Its benefits can be varied from satisfying diverse customer needs through offering customized product with reduced lead-time. This research investigates the overall concept of product modularity, its application in industry and related works published in the literature. The main objective was to identify metrics can be used to measure product modularity. Six industrial cases are investigated in this research study with the objective to measure their product modularity levels. In order to measure such modularity level, Design Structure Matrix (DSM) tool and an analytical method are used. Result shows that overall modularity level in the case industries varies significantly based on product architectures, which are related to the number of components, number of modules, and number of interfaces/dependencies.

Keywords
Product modularity, design structure matrix (DSM), modularity level, design strategy, product design and development.

1. Introduction

Product modularity concept refer to products, assemblies and components that fulfill various functions through the combination of distinct building blocks called modules. The module itself can be defined as the collection of components that are interfaced with each other for a specific function. Modular components also refer to components that are functional, spatial and other interface characteristics fall within the range of variations allowed by the specified standardized interfaces of a modular product (Cabigiosu et al., 2013). Appropriate mixing and matching of modules forms a family of product that support product variety within product portfolios. Through the modular architecture, a company can respond quickly to market changes (Huang, 1999).

The product modularity can be viewed on two design characteristics; similarity between physical and functional architecture of the design, and minimization of incidental interactions between physical components (Ulrich and Tung, 1991). Based on the interactions within a product, four categories of modularity have been defined (Ulrich and Tung, 1991):

1. Component-swapping modularity, e.g. matching of different types CD-ROMs with the same motherboard.
2. Component-sharing modularity, e.g. spark plugs, monitors can be shared/used with different products.
3. Bus modularity, e.g. USB port is bus module, which can be used with various peripherals like a flash drive, printer, mouse etc.
4. Cut-to-fit modularity, e.g. iPhone cables comes in different lengths, 1m, 2m. The main difference is that the wire length is varied, but the two standard connectors at each end are the same.

2. Literature review

Product modularity is considered as a practice of using standard modules that can share across different product lines (Tu et al., 2004; Shamsuzzoha, 2011). It uses an architecture that creates interfaces between functional components to allow the substitution of a range of components to create product varieties. Through the modular strategy, the mo dules are shared across product lines, keeping the remaining components/parts as delivered to the assembly in product lines. This result reduced product development lead-time with better-integrated designs that ultimately offer more value to the customer (Baldwin and Clark, 2000; Ernst, 2005).

Modularity can be merged with economics and exports of a country. As stated, product modularity offers the essential components to manufacture variants of products (Kamrani and Salhieh, 2002; MacDuffie, 2013). It facilitates flexibility in supply chain management through delivering modules separately when needed. It also contributes to agile assembly and enhance maintainability through predefined interfaces. Different modules are interfaced within a product architecture depending on their functionally towards the product. The principle on which a product's functions are assigned to its components is known its architecture (Ulrich, 1995). The components within a specified module are comprised with many interdependent interactions, which are generally predefined within the architecture.

Modular structure offers strategic flexibility and agility in the production process (Worren et al., 2002: Pashaei and Olhager, 2015). It integrates the interrelationships of product design, organization design, process design with effective learning and managing knowledge, and competitive strategy (Baldwin abd Henkel, 2015). It also coordinates of production processes without the tight coupling of organizational structures. Product modularity often interfaces with product and organization designs based on standardized information structure (Aversa et al., 2015). This information structure provides the required 'glue' that holds together product design and organization design (Sanche z and Mahoney, 1996: Jacobs et al., 2007; Davies and Joglekar, 2013). By interfacing modularity in product and organization designs therefore enables a new strategic approach to the information management.

3. Research methodology

This research is adopted both case study and analytical approach with the objective to measure product modularity level. With the objective to study the case industries at Sohar, Rusayl and Nizwa industrial states in Oman, six factories were filtered based on specific criterions such as the number of components, uniqueness of industry, production quantity and modular production strategy. These factories were investigated to identify their product development strategy with respect to modular or integral or both.

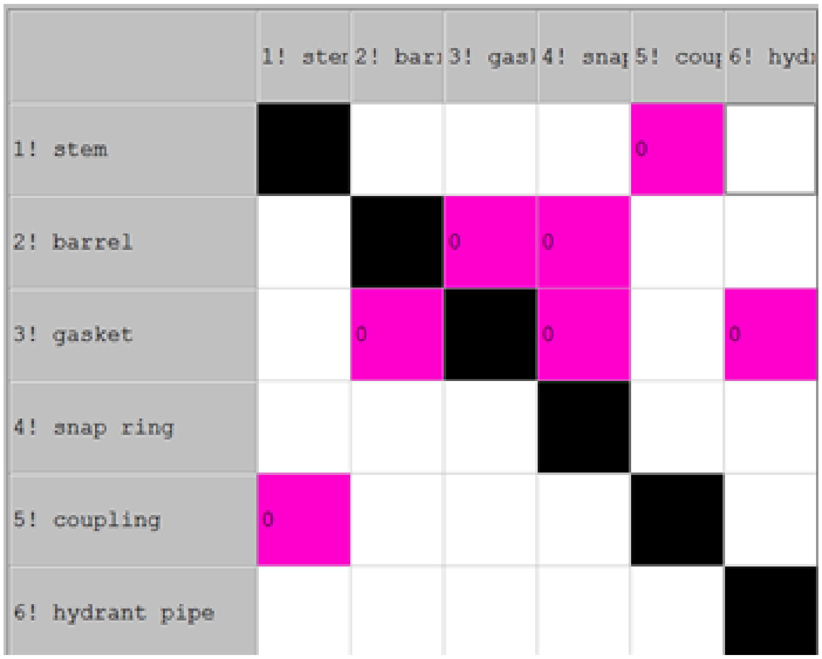
In the next phase, the case companies were investigated with respect to their modularity level through analytical model. This model uses to measure the measuring criterions such as grouping efficacy, grouping efficiency, grouping capability index and utilization rate of the components in a module.

In order to investigate the modularity within case companies' product lines, DSM tool was extensively used. This tool offers unique benefit to identify number of modules, which can be possibly developed with existing product design strategies within companies. These modules can be checked with the exiting modules if ether is any and if not how many modules can be considered in designing any specific product. The result of modularity levels of the studied companies are presented in Table 2, however, for demonstration purpose one case industry's product line is checked for modularity and the necessary measurement techniques are also elaborated in detail.

4. Design structure matrix (DSM): tool to identify module

The design structure tool (DSM) is a tool used widely to manage complexity (Steward, 1981). It is mostly used in the fields of design and engineering management, but it is also used to find and control patterns of relationships among system's elements. In addition to design issue, the DSM can also be applied to display the relation between organization's departments.

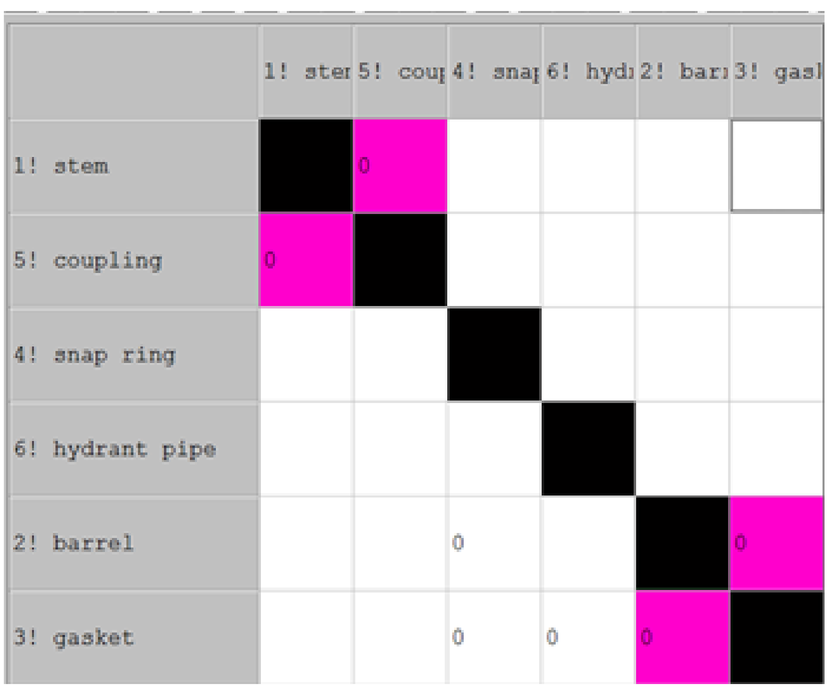
The DSM tool is a square matrix, where cells on the upper-left to lower-right diagonal represent the elements of a system and off-diagonal cells represent the interrelationships among these elements (Steward, 1981). For example, Figure 1 displays 6×6 DSM, where each row and column represents the name of the individual component. The marks at the off-diagonal cells represents the interdependencies between two or more components. For instance, component number two (barrel) as seen in Figure 1 depends on the information from component 3 and 4 (gasket and snap ring respectively) to complete its design.



	1! ster	2! barı	3! gasl	4! snaj	5! couj	6! hydı
1! stem					0	
2! barrel			0	0		
3! gasket		0		0		0
4! snap ring						
5! coupling	0					
6! hydrant pipe						

Figure 1: Display of components relation by DSM (non-partitioned)

The interdependencies of components as shown in Figure 1 can be partitioned following the partitioning algorithm within the DSM. This partitioning process also called clustering is done through grouping components depending on their closeness or dependencies on each other. The clustered DSM is shown in Figure 2.



	1! ster	5! couj	4! snaj	6! hydı	2! barı	3! gasl
1! stem		0				
5! coupling	0					
4! snap ring						
6! hydrant pipe						
2! barrel			0			0
3! gasket			0	0	0	

Figure 2: Display of components relation by DSM (partitioned)

The interpretation of the interdependencies can be displayed in various forms over the DSM. For instance, the interpretation can be in the form of numbering such as 0, or 1, dot or cross marks on the cells and empty cells, etc. In addition to such symbols for displaying interrelations, often the relationship intensity such as strong, medium and low; probability issue such as probability of a change in one element causes which percentage of such change effects on other element, etc.

5. Analytical method used to measure the modularity level

This section describes the performance metrics as used to measure the modularity level within case companies. The metrics were identified based on four criterions such as grouping efficiency, grouping efficacy, grouping capability index and utilization. The detailed of each criterions are illustrated as follow:

(a) *Grouping Efficiency:*

The grouping efficiency can be defined as the quantitative measure of goodness of component-module interrelationship within a product architecture. It can also be explained as the ability of the components to form a group or module based on their interfaces or interdependencies within a product architecture. The grouping efficiency can be demonstrated as follows (adapted from Chandrasekharan and Rajagopalan, 1986):

$$\mu = q\left[\frac{N_1}{N_T}\right] + (1\text{-}q)\left[1\text{-}\frac{N_2}{N_T}\right], \qquad (1)$$

Where, N_1 = total number of '0' in the diagonal block (module) of the clustered DSM.
N_2 = total number of '0' in outside the diagonal (off-diagonal) block of the clustered DSM.
N_T = total number of components in a specific product
q= weighting factor ($0 \leq q \leq 1$), whose value is dependent on the management personnel within a company

(b) *Grouping Efficacy:*

The grouping efficacy can be defied as the assessment of a group's or modules perceived capability to perform. It is used to assess group's performance based how many elements successfully make the group or cluster. The efficacy can be expressed as (adapted from Gibson et al., 2000):

$$\eta = \frac{1-N_2/N_3}{1+N_4/N_3}, \qquad (2)$$

Where, N_3 = total number of '0's inside and outside diagonal modules of the clustered DSM.
N_4 = total number of components participated to form module(s).

(c) *Grouping Capability Index (GCI):*

The GCI can be expressed as a measure of how efficiently the components are grouped or clustered together. This index can be expressed as (adapted from Seifoddini and Djassemi, 1994):

$$\text{GCI} = 1 - \left[\frac{N_2}{N_3}\right], \qquad (3)$$

(d) *Utilization rate:*

The utilization rate can be expressed as the rate of components that are formed group or module. The higher the value of utilization, the better the components is used to form necessary module(s). The utilization rate can be presented as (adapted from Chandrasekharan and Rajagopalan, 1986):

$$\text{U} = \frac{N_1}{N_T}, \qquad (4)$$

6. Case example

In order to demonstrate the modularity level, one industry was selected and elaborated as case example. The case industry as selected is one of the leading engineering companies based in the Sultanate of Oman involved in steel fabrication and machining activities. The company manufactures all types of gears and gearboxes including – spur / helical / worm reduction / straight bevel and spiral bevel drives. The gears are manufactured on precision gear machinery and in house heat treatment facility for hardening the gears manufactured by the company. Figure 3 shows some sample of case company's gears and the list of components with the gear is presented in Table

Figure 3: Case industry's product: gear

Table 1. List of components of case company's product

Serial number	Component name	Serial number	Component name
1	Hand wheel	14	Oil ring
2	Press ring	15	Shaft
3	Dish spring	16	Key
4	Stop ring	17	Bearings
5	Driver	18	Gear
6	Oil seal	19	Control
7	Planet wheel	20	Ball ring combiner
8	Veriator casting	21	Pin
9	Rectangular seal	22	Gear box
10	Oil-loil-plug	23	Speed control cam
11	Oil breather	24	Fixed ring
12	Control socket	25	Fixed cam
13	Oil plug		

6.1 Status of product modularity within the case industry

In order to measure the modularity level within the case industry, the DSM tool was used to identify the modules. The modules were identified based on the collected components of case industry's product and their interdependencies between each other. The interdependencies between all the 25 components are presented in Figure 4. The components above the diagonal line indicate the interdependencies on other components. For instance, component 1 (hand wheel) cannot be completed its design until it know the necessary information from component 23 (speed control cam) and so on.

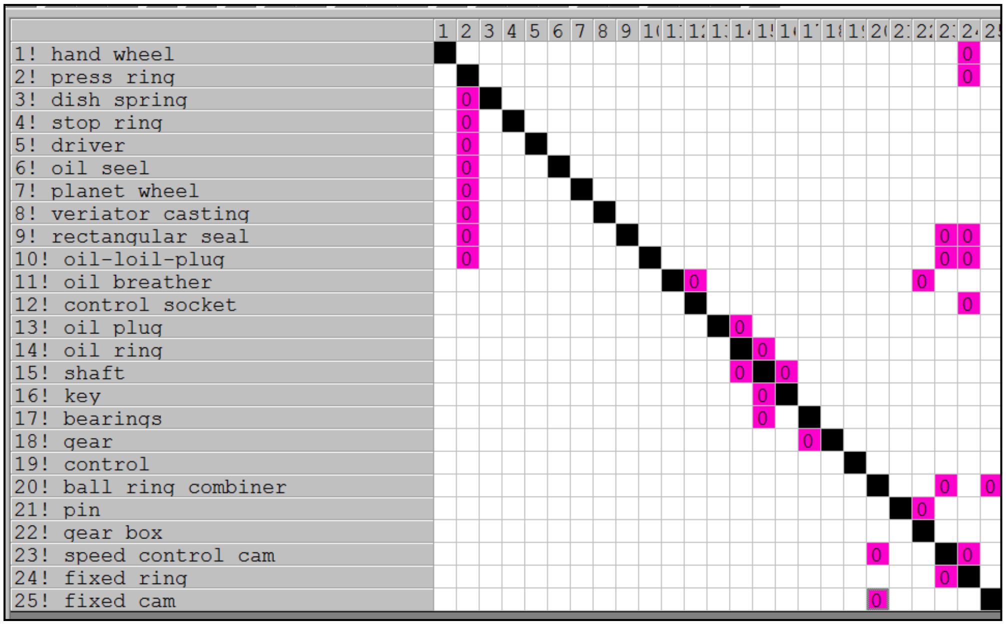


Figure 4: Components interdependencies within the case industry's product (gear) (un-clustered)

The components interdependencies as presented in Figure 4 is partitioned following the DSM clustering method and the resultant modules are highlighted in Figure 5. From Figure 5, it is noticed that only two modules are identified out of 25 components in total. It can be also noticed from Figure 5 that except the components within the two modules, rest of the components are below the diagonal line, indicating that the components are sequentially organized. It means that each of the component design does not need to wait or depend for any information on other components. This sequential designing support product designer to reduce developmental lead-time.

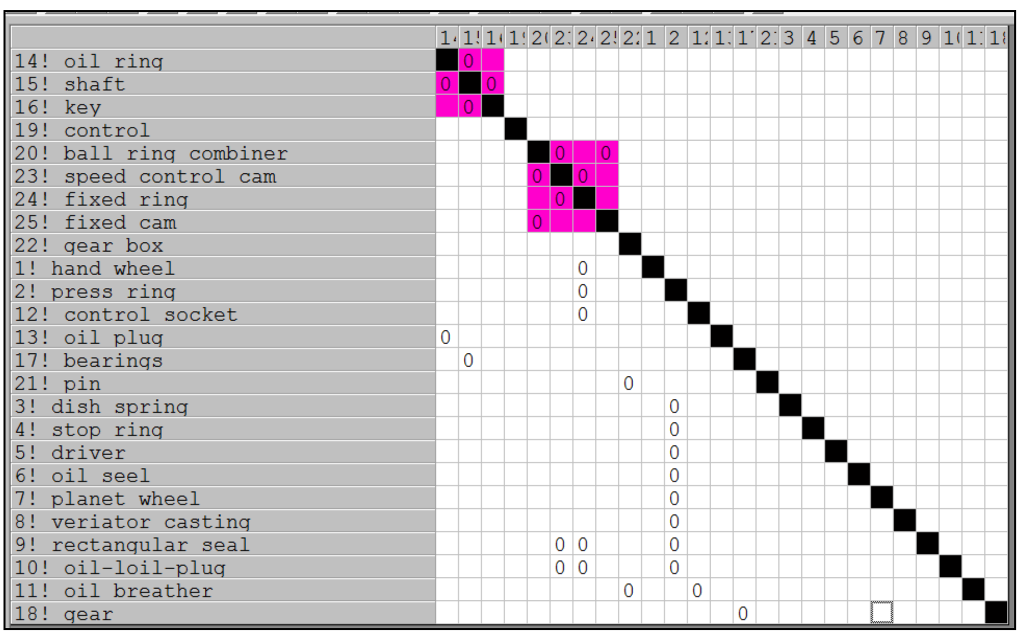


Figure 5: Components interdependencies within the case industry's product (gear) (clustered)

6.2 Measurement of modularity level within the case industry

The modularity level within the case industry was measured using Equation 1, 2, 3, and 4. From Figure 5 following data was calculated which are used to measure the modularity level.

N_1=10, N_2= 21, N_3= 31, N_4= 7, N_T=25

Applying Equation 1, the grouping efficiency is calculated as:

$$\mu = 0.5\left[\frac{10}{25}\right] + 0.5\left[1 - \frac{21}{25}\right] = 0.28 = 28\%$$

Grouping efficacy is calculated using Equation 2 as:

$$\eta = \frac{1 - 21/31}{1 + 7/31} = 0.26 = 26\%$$

Grouping capability index (GCI) is calculated using Equation 3 as:

$$\text{GCI} = 1 - \left[\frac{21}{31}\right] = 0.677 = 67.7\%$$

And utilization rate is calculated by applying Equation 4 and the outcome as:

$$\text{U} = \frac{10}{25} = 40\%$$

6.3 Outcomes from case industry's modularity level

The results from the case industry's give several intrinsic decision factors, which may need more attention.

(i) The grouping efficiency of company's product line seems very poor (28%), which is above below 50%. It indicates that the components within the two identified modules are poorly grouped or tightened with each other.
(ii) The grouping efficacy is calculated as 26%, which seems very poor in general. It indicates that the overall capacity of the components to form group or module is poor.
(iii) The grouping capability index (GCI) is calculated as 67.7%, which seems satisfactory (above 50%). It indicates that the grouping capability of the components within the two identified modules are fairly good.
(iv) The utilization rate of the components to form the module is 40%, which is identified as poor outcome. This outcome indicates that the utilization rate of the components to form the expected modules is not satisfactory, meaning that the design of components interfaces are needed to be revisit in order to develop more modules and not just only two for this specific case industry.

6.4 Reasons for low modularity level in the case industry

The reasons behind the low level of modularity in the case industry can be interpreted in different ways. First of all, the reasons found out that there is a lack of knowledge of modularity and its accompanied benefits in the case industry. Secondly, it is often very difficult to change any product development strategies due to cost involvement, support from top level personnel. The…..Omani industrial sector about the product modularity and its significance in the manufacturing process and how it would facilitate the manufacturing process and reduce the associated costs. The type of products produced in Oman is also a big factor for having a low level of modularity because most of the products produced are mainly in the food and medical industries in which they required unchangeable sequence of process.

Also the production of most of the industries is oriented toward customization because the need of its market. As for other companies they are importing main components of their final product and just working on the process of assembling these components, without adding any value into the product. Moreover, big number of the companies are producing non-complex products resulting in reducing the opportunity of having modular products. As for the factory strategy of product Research and Development Department, no factory has been encountered to have a department that is dedicated to Product Research and Development. This means that the product will follow the same manufacturing process with no development, resulting in no possibility of product modularity.

7. Research outcomes and limitations

The case industry's modularity level as explained above is not much encouraging. It indicates overall poor performance with respect of product modularity. The overall product modularity metrics for other five case industries are presented in Table 2. From Table 2, it is noticed that some case industries measurement modularity levels are quite good and some are poor. For instance, case industry 2, 3 and 6 shows higher grouping efficiency and utilization rates, while case industry 1 and 4 show fairly good and case industry 5 shows poor modularity metrics.

Table 2. Comparison of modularity metrics for 6 studied case industries

Case Industry	No. of component	*No. of module*	*Grouping Efficiency, μ (%)*	*Grouping Efficacy, η, (%)*	*Grouping Capability index, GCI, (%)*	*Utilization rate, U (%)*
1	22	3	58	17.4	06.87	17.58
2	11	3	74	60	75	54.5
3	6	2	70	57	57	50
4	13	2	61.1	25.6	91.67	24.7
5	25	2	28	26	67.7	40
6	10	1	76.7	33.3	33.3	66.7

From above analysis, it is noticed that in order to improve modular design strategy within companies, it is necessary to revisit their product design and development scenarios. It is always recommended to change the product design as much as possible from traditional integral design to modular in order to achieve inherent benefits.

7.1 Research limitations

During conducting this case study, authors faced several limitations, which may affect the research outcomes. For instance, during the process of collecting data, several tackles have been encountered. It has been difficult to scan and go through all the factories of the industrial estates and identify which factory would fit the intended research and have the potential of modularity. It was also difficult to find the companies, which are practicing product modularity in their product portfolios. Several occasions it was found that some industries were not concern about the benefits of modularity but following their traditional design philosophies in products development.

In such scenarios, it was needed to explain the concept of product modularity and its accompanied benefits within the case industries and to motivate them to deliver relevant product design data for their own benefits in future. Furthermore, the data collection process was concentrated by asking design related questions to the design engineers and manufacturing engineers, which might often give error data due to personal bias. The components dependencies also may be misinterpreted due to the absence of original design architecture. Some the case industries were quite far locations, and get permission to enter and collect data.

8. Conclusions and future works

Modular product development is attracting more attention within industries with the aim to achieve better product or process design. This attention is driven from the benefits drawn from modularity. The modular design strategy offers added benefits over integral design. The modular design ease the assembly process, changeover, re cycling, repair and maintenance, etc. It offers flexibility in supply chain and ease of product packaging and delivery too.

Other advantage of modular product design and development is that same module can be used in different products to offer product variety. The development of product variety enhances mass customization with reduced lead -time and production cost. This strategy also reduced complexity in design and engineering.

The application of DSM tool helps design engineers in industries to identify modules in their product liens. This tool is used in this research study not only identifying modules but also measuring the modularity level. The modularity level is measured through four metrics namely grouping efficiency, grouping efficacy, grouping capability index and utilization rate. The studied six case industries highlights different results. Some industries are quite good in modular design issue, while others are not.

In order to improve modularity in industries, it is recommended to take initiatives such as revisit their corresponding product design and manufacturing strategy, redefining component interfaces, cross checking with design and manufacturing department, enhance information flow between design and engineering, etc.

Future research will focus on analyzing modular measurement in more industries with the objective to generalize the outcomes. Additional metrics such as …can be investigated to measure modularity level in product design and development.

Acknowledgements

This research is funded from Internal Grant Project (Project No: IG/ENG/MIED/16/03). Authors like to thanks Sultan Qaboos University to funding this research. The authors sincere thanks also go to the industries who supported this work through providing necessary data and/or information.

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