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An Integrated Approach in Designing Modularity for End-of-Life Vehicle Recovery

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A**BSTRACT---- Appropriate *handling of end-of-life vehicles is necessary in addressing environmental sustainability. To date, a number of methods and measures for designing and developing modular products have been generated, aimed at facilitating the separation of parts/components into independent modules for reuse, remanufacturing and recycling. This paper review and analyses existing methods and measures for product modularization that deal with product complexity in terms of product architecture, functionality and design. An effective method must be able to verify and validate the proposed modularization process and their results. Therefore, this paper presents an on-going research for a practical and integrated approach for modularity optimisation based on qualitative and quantitative measures capable of validating the developed modules. Findings from the study which was conducted on a national car door assembly can be used to further enhance the design for ease of reuse and remanufacture.***

Keywords--- Modularity, Automotive Component. Reuse, Recovery

1. INTRODUCTION

Increasing pressure and challenges from legislation and regulations has led to consciousness on environmental protection among manufacturers leading to numerous proposals on life cycle and recovery strategies. Product recovery is described as a set of activities to reclaim value at the end-of-life of whole products for reuse purposes by remanufacturers [1]. For the purpose of recovery, the term 'reuse' has been dominated as the main activities for product life extensions before allocating it to sub-activities namely repair, reconditioning, remanufacturing and recycling [2]. It is aimed at recovering possible parts/component from obsolescence when it reaches its end-of-life. Unfortunately, due to short technology cycle, a product must be designed with reuse properties which will enhance the recovery percentage at its end-of-life. Technology, software upgradability and relevant reused methods must be available to overcome issues related to obsolescence which can be addressed through modularization.

2. MODULARITY

The term 'modularity' has gained significance over the past two decades. Modularity can be defined as the decomposition of a product into sub-assemblies and smaller components. It is dependent on two characteristics: similarity between the physical and functional architecture of the design and the minimization of incidental interactions between physical interactions [3]. The modularity concept is aimed at separating a system into independent modules and treating it as logical unit [4]. Specifically, modularity is a term that refers to products, processes and resources that fulfill various functions through the combination of modules, and this concepts have been widely used in different industry, from manufacturing (modular fixtures, modular machines) to the design of electrical and mechanical products and software [5].

2.1 Advantages and Barriers of Modularity

The advantages of the modular concept is that it enables module to be produced, assembled, and tested at convenient locations with proper equipment, tools and expertise [6]. In fact, by carefully modularizing a product, the design of the earlier models can be used in a new model without any changes or simply adding additional and auxiliary mo dules to create another new model, as some components can be used across product variants and product lines due to standardization of the functions and interfaces [7]. The performance measures, such as time, cost, reliability, quality and manufacturability can be enhanced by optimizing the three models, namely the products, process and resource [5]. Moreover, modularity allows economical modification and maintenance, remanufacturing and adaptation by changing defective and obsolete modules as well as the product configuration as it did allow multiple use phases of a products and modules in different applications for different markets [8]. With a good modular design and proper selection of materials for remanufacturing/production, separation effort will be more efficient and cost effective.

Despite all these advantages, there are still numerous issues or obstacles for an effective modularization of products. A review on modularity practices have been put forth by [5] highlighting concerns on the narrowness of the domain such as poor understanding on modularity issue, lack of theory and tools for the definition of modules from a broad perspective, including some designers' skepticism of its advantages since the benefits have yet to be demonstrated. Customer acceptance of remanufactured products after undergoing maintenance/recycling stages in the modularization process must also be considered. This is due to a lack of awareness and uncertainty on the quality of remanufactured product to be worth purchased. Fortunately, the past few years have seen a clearer perspective on the benefits of modularity. The increase in environmental awareness and demand for recovery legislation have driven automotive component manufacturers around the world to practice automotive component reuse at their end-of-life [9]. With respect to ecological and economical risk [8], the frequency of modules changes due to technology fresh up and maintenance has increased resource consumptions especially for limited number of functional used parts. With frequent module changes, high cost and time intensive efforts are required for the initial development of product structure for new product generations. Additional costs may be incurred due to subsequent changes in the product structure. Even through modularity design and recovery, by the time it is ready to be reused, the embedded technology may have been obsolete, and no more valid to customer needs.

A survey conducted by Hammond et al. [10] has indicated that the major factors causing a product to be difficult for remanufacturing are parts availability and parts replacement. Due to the rapid growth in technology, the market nowadays seems to compete by serving a variety of products. Logically, even if the total product volume is still high, but under circumstances, the variety of the products has caused a decrease in the parts production. Hence the availability of the parts has become narrower and the cost of parts replacement will increase automatically [10].

3. METHODS AND MEASUREMENT OF MODULARITY

Measures and methods for modularity vary, depending on the type of product, purpose and process. Some of the methods are highly quantitative while some are completely qualitative [11]. It is noticeable that most of the methods are focusing on the measures of dependencies and similarity between modules. However, there is no specific record on methods to represent the product modular information for designing modular products. The following sections will address a number of established methods and measurement of modularity that will be applied in this study.

3.1 Modularity Metric

Life cycle modularity metric is introduced to generate product architecture analysis for redesign purposes [4]. The hypothesis of the work is that a high degree of life cycle modularity can be beneficial across the interest of functionality, recycling, post life intent and services viewpoints. The related life cycle characteristics is defined as material compatibility and separation effort for recycling, servicing frequency for service while for post life intent, the relevant characteristics named as the final destination intended for each component after reaching their end-of-life, either recycling or reuse. The analysis is done based on the previous work where two measures of modularity evaluation are proposed [12]. First is to measure module correspondence between several viewpoints (known as correspondence ratio, CR) and second is to measure coupling between modules (known as cluster independence, CI). An automotive interior, the center console, together with instrument panel and center module has been chosen as a case example in [4] and [12]. Before measuring the modularity metric, the product architecture or modules must decomposed first. To do so, a systematic method, Design Structure Matrix (DSM) is applied. It is used to determine actual degree of correspondence between viewpoints. It is noted that the value of modularity ranges between 0 and 1. The higher the value, the more modular the product is. This method is meant to guide a redesign process. Hence, it is better to start by focusing on primary modules and its structure before going deeper into the post life intents of each component. Besides, it is more convenient to propose minor changes based on the original design first and studying their effects before exploring into the broader product changes of the overall structure. A good tutorial of the method is given by Newcomb et al. in [4] and [12].

3.2 Module Interaction Matrix

A method considering various life cycle engineering objectives such as assembly, maintenance, reuse and recycling to stimulate modularity is discovered in [7] and can be approached in two ways: 1) Forming modules based on each objective separately and then making trade-off decisions between different modular configurations and 2) Modularizing a product based on weighted average objective.

The proposed method consists of three main phases: problem definition, interaction analysis and module formation. The case study examples are vacuum cleaner and starter in [7] and [13]. This method starts by identifying the type and characteristics of the design problem, then decompose it into sub-problems and determine the objective of modularization. Noted that for original design, the design knowledge is actually in the form of functions, thus the decomposition determines the functional structure of the product. On the other hand, for redesign or adaptive design where the physical solution is already known, the decomposition is the identification of physical components or sub-systems within the product (physical structure). Interaction analysis attempts to cluster components into modules where the interactions between modules are minimized. The designers must identify relevant interaction factors for each of the identified modular objectives for the product to be modularized. A list of relevant sub-factors for modular objectives of vacuum cleaner and starter can be found in [7] and [13]. To evaluate the interactions of the objectives, the values of interactions among components must be determined and gathered in a so called interaction matrix. After the interaction matrices were prepared for all the factors, the corresponding matrices were combined for each objective. W ith all the matrices established, the final combined interaction matrix was created for module clustering. The clustering process is carried out using several algorithms in order to get modules with integrated objectives. For more information about this method, refer to [7] and [13].

3.3 Design Structure Matrix (DSM)

DSM is very popular in representing analysis for product modularization and several types of system or product architecture. DSM consists of three main steps [14], namely:

1. Decompose the system into elements - describe the product concept in terms of functional and/or physical elements which achieve the product's functions.
2. Document the interactions between the elements – identify the interactions which may occur between the functional and physical elements.
3. Clustering the elements into chunks – cluster the elements into chucks based on criteria set by the overall product design strategy of the team. These chunks then define the product architecture and system structure.

DSM is a square matrix with component and functions placed on the identical row and column labels and their interactions are marked in matrix [15]. All four proposed interactions; namely spatial, energy, information and material as defined below are scored with a five point scale (-2 to +2), depending on the strength of the relation [16]. There are 2 categories of DSM so called static and time based [17]. Static DSM is representing the system elements such as product architecture or groups in an organization and analyzed with clustering algorithm. While time based DSM indicates the activity flow through time and is typically analyzed using sequencing algorithms. Obviously, DSM is specially design for complex architecture which concentrates more on the interfaces or interactions between modules in order to simplify the design process and the complexity of product architecture. It is a very useful tool for decomposition but to gather precise data to build a DSM model is not easy. Moreover, since there is no limit to the DSM size, the DSM with larger elements is difficult to integrate, analyzed and presented as a single element with minimum loss of information during the integration process. Perhaps DSM with larger elements can be integrated with smaller DSMs in order to build a DSM model. For better understanding, refer to [16] and [17].

3.4 Modular Function Deployment (MFD)

Modular Function Deployment (MFD) consists of five major steps and purposely designed to modularize a single product [18] and [19]. This method is based on module drivers as the driving forces for modularization, which enables the grouping of independent assembly for each module that can be adapted precisely to actual module. Details of MFD steps can be referred in [18] and [19]. Originally, there are six module drivers in [19] before it is expanded into twelve module drivers as pointed in [18]. The first module driver in the latest version is carryover, a specific part/subsystem of a product that is carried over to a new product without any changes to it. Second is technology evolution and third are the planned product changes. Both has similarity where products will undergo changes either due to changing customer demands, technology shift or company development plans. Next is the different specification where product variation and customization is enabled. Styling is an influence factor for the appearance of a product and depends on current trends. Common unit modules that refer to parts/subsystem can be used for the entire product and implies large production volumes. Production process, separate testing, supplier availability and service and maintenance are related to the processes for modularization. By doing separate testing of each components before reaching final assembly process, and followed with good service and maintenance when using the product, the product quality may be enhanced. Upgrading allows future additions to products for improvements and lastly recycling is considering the after-life of the products.

This method is indeed focusing on the evaluation phases, where each criterion represents different levels of the product life cycle objective. The module drivers are identified as the best tools to integrate and group modules for optimization of modularity. The original MFD has suggested specific steps where three types of interfaces are considered, namely fixed, moving and media attachments, as well as forces, energy, materials flow and signals transmission. In addition, several economic factors should be taken into consideration, for example; the Activity Based Costing (ABC) analysis. Even though this method emphasizes evaluation, it does not provide a variety of evaluation tools. Perhaps with some addition of engineering design tools and critical design criteria for verification purposes such as Design for Manufacture and Assembly

(DFMA), optimal results of modularization and design improvements can be obtained.

4. CURRENT WORK

From literature study, it is found out that each method has its own scope, strengths and limitations, and the choice of the method to be used is dependent on the application, way to implement and the complexity of the product itself. An integrated method that combines MFD and extended with DSM, interaction matrix analysis, modularity metric and other relevant engineering design techniques will be proposed. The integrated method will capable to conduct better analysis on modularity as each methods chosen has their own benefits and purposes to serve various aspects of life cycle viewpoints.

An evaluation of the final outcome will be carried out using the modularity metric. For the purposes of this study, a car door assembly will be used as a case example. The integrated model proposes three main phases and eight steps for its implementation. The three main phases, namely: product decomposition, interaction analysis and module formation/clustering. To start with, the type and characteristics of the design problem must be identified first, followed by detailed elaborations on the product and then proposing possible objectives for modularization purposes. As for the second phase (interaction analysis), functional interactions will be defined, including the relations among sub-factors for each objectives and technical solutions. Phase 2 is vital for reducing the complexity of the modularization process. Phase 3 emphasises pre-structuring and clustering the modules. The outcome of clustering will then be verified using modularity metric and some other design tools. For better understanding of the method, please refer to Table 1.

To date, three main modular objectives have been classified (adapted from [7]). The first objective (reuse/remanufacture/recycling and disposal), consists of eight sub-factors namely: attachment/alignment, exchange of force/energy and signal, life expectancy, reusability, component worth, remanufacturability, recyclability and homogeneity. Meanwhile, service and maintenance has been selected as the second objective and has four sub-factors, namely: the frequency of failure/service, the requirement of skilled personnel, tooling/fixtures and repair time/down time. The third modular objective is assembly. It has only two sub-functions, which are the attachment/alignment and assembly sequence/ handling. Later, each of the sub-functions will be assigned with interaction scores to indicate the relations intensity among the components before converting it into matrix. Each of the sub-factors matrices is later combined into one integrated matrix, named as the Average Weighted Interaction matrix. For more details on the flow of interaction analysis process, please refer to the illustration in Figure 1 (for service/maintenance objective) and Figure 2 (for combined all objectives).

Table 1: Summary of proposed integrated method

Phases	Details
Product Decomposition	**Step 1**: Identify the type and characteristics of the design problem (in terms of the functional structure). Tools: Modified QFD as in MFD method.
	Step 2: The product is decomposed into components and lists of components are included. Tools: Assembly diagram and component list.
	Step 3: Elaborate in detail each of the possible objectives for modularization. Tools: Modular objective lists.
Interaction Analysis	**Step 4**: Identify all functional interactions. The objectives are decomposed into functions (or factors) and sub-functions (or sub-factors). A table is created to assign values for degree of importance for each of the selected interaction factors. Tools: checklists, hierarchy of objectives, functions and technical solution mean tree.
	Step 5: Assigning values for interactions/technical solutions for comparisons and better results. Tools: Interactions Analysis Matrix, The average weighted interaction and Module Indication Matrix (MIM).
Module Formation/ Clustering	**Step 6**: Module clustering. Tools: Clustering algorithms.
	Step 7: Evaluate results of module clustering. Tools: Modularity metrics.
	Step 8: Design tools for results verification. Tools: Failure Modes and Effect Analysis (FMEA) and Maximost Software.

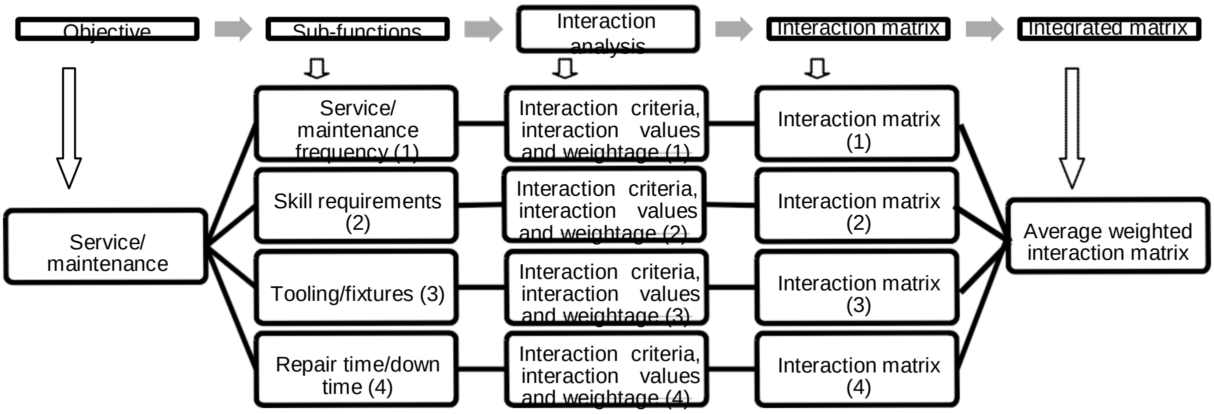

Figure 1: The proposed process flow for interaction analysis for car door service/maintenance objective.

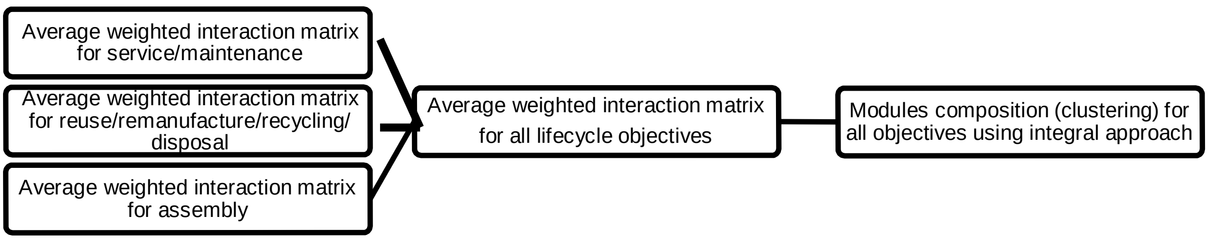

Figure 2: Interaction analysis for the combined objectives

Table 2: The evaluating criteria for reuse/remanufacture/recycling/disposal objective

Sub-factors	**High**	**Medium**	**Low**
Life expectancy	> 10 years	5 ≤ 10 years	<5 years
Reusability	Not even contact	Fasteners	Permanent attachment
Component worth	> RM100.00	RM50.00 ≤ RM100.00	< RM50.00
Remanufacturability	mponents which are easily reused by reassembling	work need to be done before reusing	machining is required before reusing.
Recyclability	Easily recyclable and high intensive	Not easily recyclable but high intensive	t easily recyclable and no incentive for recycling
Homogeneity	Only one material	One major and small amount of another material	Multiple materials

Source: Adapted from Gu and Sosale (1999) [7]

An example of the evaluation criteria for each of the sub-factors for reuse/remanufacture/recycling and disposal objectives are shown in Table 2 (Adapted from [7]). After establishing the evaluation criteria and classifying the components, the interaction scores are then assigned. The interactions are graded with a score system using values ranging from '0 to 4' for weak relation, '4 to 7' for medium relation and '8 to 10' for strong relation. Using this information, the interaction values between the components are then assigned. Later, all the matrices for sub-factors are combined into a final integrated matrix and are ready for module clustering. Table 3 shows the integrated matrix for reuse/remanufacture/recycling and disposal objective where numbers 1 to 16 represent components of a car door (modules). A detailed calculation for components 1 & 2 (as shown in Table 3)is presented in Table 4. The weightage in Table 4 is obtained from [7]. To view easily, the analysis result is rounded as shown in Table 3 and Table 4. It is noted that the majority of the relations are concerned with attachment as it relates to interfacing and connections between the components themselves. For verification purposes, the clustering results obtained later are evaluated using modularity metric and some other design tools. For more information about the details of modularity metric calculation, refer to [4].

Table 3: Integrated interaction matrix for reuse/remanufacture/recycling/disposal objective of a car door

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	10	7.80	8.95	5.85	6.50	8.75	7.70	4.80	6.50	4.95	4.95	8.70	8.45	8.05	8.05	4.95
2		10	8.55	8.80	8.80	8.75	7.10	8.10	8.80	8.70	7.90	8.50	8.80	8.05	8.05	8.15
3			10	8.95	8.65	7.10	6.25	7.00	7.90	5.80	5.00	3.30	3.45	3.60	3.45	5.80
4				10	8.65	5.05	7.00	3.90	8.65	5.95	3.60	6.90	6.30	5.65	5.65	5.95
5					10	7.50	8.30	8.15	8.35	7.75	6.95	6.45	4.65	3.45	3.45	6.95
6						10	8.65	7.80	9.00	4.65	4.65	5.55	5.60	4.35	4.35	4.65
7							10	7.80	4.65	5.75	5.60	5.90	5.60	4.35	4.35	4.65
8								10	6.15	5.75	7.05	7.50	4.10	4.35	4.35	3.95
9									10	7.45	7.05	6.45	4.65	3.45	3.45	6.95
10										10	8.20	3.45	3.55	8.00	8.00	8.40
11											10	8.05	7.45	8.00	8.00	8.60
12												10	7.70	8.00	8.00	8.90
13													10	8.85	8.85	8.60
14														10	8.60	8.50
15															10	8.50
16																10

Table 4: An example of calculations for component 1 & 2 for reuse/remanufacture/recycling/disposal objective of car door

Component:	**1 & 2**		
Interaction criteria	**Interaction values**	**Weightage**	**Total**
Reusability	8	0.30	2.40
Attachment /Alignment	6	0.30	1.80
Exchange of force/energy and signal	6	0.10	0.60
Life expectancy	9	0.15	1.35
Component worth	9	0.10	0.90
Remanufacturability	3	0.05	0.15
Recyclability	9	0.05	0.45
Homogeneity	3	0.05	0.15
Total interaction/weightage			**7.80**

5. DISCUSSION

This paper provides an overview on the measures and design methods in the current product modularity research. Each method has its own strength and benefits. The application of modularity methods are not straight-forward as it involves the interactions of a variety of criteria, task requirements, conflict resolutions and costs implications. Clearly, all these methods have a similar objective, to cluster the components into modules. First, the goals in applying the modularity methods must be clarified. Is it purposely done to optimize the existing modularity or to improve the modularity of a new design? Differences lies in the implementation phase[11], appointing the appropriate lifecycle objectives will lead to a successful modularity practice. Some of the methods focused on various crucial information and criteria such as interfaces between modules and afterlife services (as in MFD) or types of interactions and attachment (as in DSM). The MFD method is more focused on the management aspects instead of engineering design prospect. Its likely focuses on various strategic issues as in the module drivers. The MFD is also best suited for strategy based modularization [15], to define the design variants and forming more technical modules.

Since MFD does not address repeatability, DSM is combined into the proposed method as DSM can be run by a computer using some algorithms, hence repeatability and handling of complex product architecture are possible. DSM can also be used as an interface or interaction simplicity. The only weakness of DSM is it has no limitation in size and may lead to lack of human reasoning mind. It should be noted that DSM is actually one of the common tools in modularity that applies matrices as a medium to verify modularity. Matrices are purposely developed to show the dependencies or similarities between two modules, as well as the functional, assembly and disassembly connections where the strength of these relations are shown. The difference between MFD and DSM is that the latter does not discuss the variety of possibilities to optimize modularity and it does not pose any limitation on the size of the matrix which may lead to complexity of product structure. During the modularization process, most of the methods tend to minimize the number of modules, hence reducing the complexity of the product architecture. All the combined methods are very different to each other, but the goal of each method is the same, to propose better modular design.

The life cycle option or objective for each module is emphasized respectively before combining and clustering for modularization. To define the intersection between modular objectives, the interaction matrix analysis is added for module clustering later. Then, all the results obtained previously will be verified using some other tools like modularity metric, Failure Modes and Effect Analysis (FMEA) and Maximost software to assess and predict disassembly time. A solid foundation in gathering information is a priority at the beginning of the modularization process and significant amount of information such as input, signal, calculation and interactions are required for modularity verifications. Unfortunately, not all required information is readily available. Generally, modularity methods are successfully implemented for high intensive product development improvements, such as electric and electronic devices and vehicles products. An approach using module drivers as the driving forces for design improvements should be commended as it helps in the evaluation phases, starting from the development stage until the finishing stage. The interaction values were assigned for certain criteria and have facilitated individual changes in modules and quantify the strength of relationships. New approaches and measures to clarify modularity has been proposed by some researchers, such as corresponding ratio between two components, module density as the ratio of volume components to approximate module structure by evaluating geometric stability and interaction between modules. Researchers are now keen on green lifecycle issues and this will have a direct impact on the future of modularity methods and measurements.

6. CONCLUSION

This paper is meant to give an overview of comparison in the existing modular methods and measures. Three methods have been reviewed and analyzed in view of developing a new integrated approach for modularity optimization in terms of reuse and remanufacturing. The review indicates that further quantitative research is required in order to combine the strength of the existing modular methods. The goal is a combination of various relevant methods that results in a verifiably better measures and method for modularizing a product design. Hence, a solid foundation from the existing methods and measures is used to build a feasible modular design method that is capable of analyzing multiple life cycle modularity objective and criteria apart from the complexity of product itself. Future works will emphasize on Phase three, focusing on pre-structuring and clustering the modules where later will be evaluated using some engineering design tools and measures such as modularity metric, Failure Modes and Effect Analysis (FMEA) and Cambridge Engineering Selector (CES). To conclude, the choice of modular methods is dependent on the modularizing objectives itself and the architectural complexity of the products. It is hopeful that findings from this modularity study can contribute towards product design improvements for environmental sustainability.

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