Development of a framework for Disassemblability Design Optimization for Sustainable Manufacturing

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Abstract.*Sustainable Product development is seen as an inevitable solution in protecting the environment. Among the important strategy in sustainable product development is through product recovery by closing the loop. Product recovery enables the reuse of depleting source of virgin material as well as avoiding the accumulation of solid waste. Maintenance can be also considered as a strategy towards sustainable product by prolonging product life time. The success of product recovery and maintenance is highly dependant on the time and cost efficiencies of the disassembly process. This paper reviews the various methods used to evaluate disassemblability. The development of the methods and its application are reviewed to provide an understanding of any missing links that have hampered the wider implementation of disassemblability design evaluations. The paper then proposes a disassemblability optimization model that can provide the missing link between design and disassembly*

Keywords: *design for disassembly, design evaluation, design optimization*

1. INTRODUCTION

Sustainable Product development has been a key issue in recent years especially with a greater awareness in the depletion of natural resources and environmental degradation. The heighten awareness is intensified with the introduction of various regulatory measures to ensure sustainable development such as End of Life on Vehicle (ELV) Directive, Energy Using Products Directive and Waste of Electrical Electronic Equipment (WEEE) Directive would make compliance as necessary requirements for putting a product into the market. In order to remain competitive, manufacturers must actively make efforts to ensure product compliance. The growing concern of solid waste generation throughout the world is also of great impact whereby many countries have some form of legislations to control the generation and management of solid waste. Production waste has had over burden effect on the landfill cost that leads to municipalities in some countries to introduce waste tax for producers and consumers. Among the main strategies in sustainable product development is through product recovery which is relevant in almost all sectors. It does not only benefit by reducing ecological impact but it also have positive economic impact to industries [1]. Product recovery is defined as the activities that lead to the salvaging of material and energy of products at its end of life . Another form of strategy in ensuring waste generation at its minimum is through prolonging the life of products through proper maintenance. By having proper maintenance, it would not only prolong the lifetime of a product, but also reduces emission caused by product wear and reduce inefficiency. Both of these strategies depend on the products ability to be disassembled, disassembly for maintenance and disassembly for end of life [2][3]. The introduction of product service supply (PSS) have led to the need for better components salvaging for remanufacturing which is the critical process in the success of PSS. Similar to assembly planning and production planning, the disassembly process also highly depends on the design of the product.

Disassembly is a process in which a product is separated into its components and/or subassemblies by non-destructive or semi destructive operations [4]. The term disassembly can be viewed from two

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approaches, which are disassembly for maintenance activities and disassembly for end of life activities where both are desirable in terms of the ecological impact. The reasons are largely grouped into disassembly for maintenance and disassembly for end of life.

Disassembly for maintenance is the removal and subsequent reassembly of parts in order to prolong the life of the product, hence reducing the need to process new materials and maintaining optimum efficient work condition of the machine. Disassembly for EOL on the other hand is the removal of parts to extract parts for reuse/remanufacture or material extraction for recycling. Extraction for recyclable material is most often by destructive methods, while extraction of parts for reuse and remanufacture must be non-destructive. This is the main reason for the limited success in reusable and remanufacturable products as removing parts without damaging it is often a tedious, time consuming and cost inducing process with low value. Disassembly for remanufacturing would not be cost effective and efficient if parts are difficult to be removed. Recycling disassembly is sometimes necessary in order to separate parts of different material and to reduce the size of a product or subassembly to ease the shredding and separation. Assessing and designing for product disassemblability is thus an important issue.

To ensure product can be disassembled effectively and economically, product must be designed to have such features. Several studies have noted that design decision contributes 70-80 percent of total product cost [5]. This is also true for disassembly cost as decision made during designing could cause difficulties in disassembling thus cost more to disassemble. Most studies concur that adoption of design for disassembly must be at the early stage of the development process as early as conceptual stage [6]. Thus, it is important for engineering designers to design with cost efficient disassembly in mind to enable the product to have a better EOL strategy.

2. PRODUCT DESIGN FOR DISASSEMBLABILITY METHODS

Several studies were carried out to develop methods to evaluate product design for disassemblability such as by [7][8] which are described in the review below. Several works that deal with optimization of design disassemblability are included as well. As the term disassemblability is often associated with the removal of fastener, so several studies on fastener selection for disassembly are also included in the review below.

Through the MOST empirical data [9] had found that the disassemblability of a product depend on the accessibility of the parts, precision required for positioning a tool, amount of effort for a task and the base time for basic task movements without difficulties. Based on their findings [9] developed a disassembly task difficulty score based on the MOST predetermined time system that broke down all of the tasks into their basic elements. The method provided for 16 standard operations such as unscrew, cut wedge, etc, that would cater for the disassembly of medium size products. The types of tool were also considered in determining the part removal difficulty.

Research by [10] used the MTM system for its basis of determining disassembly difficulty. Each disassembly task was empirically studied in greater details and scores were assigned based on the MTM values. The method included force requirement, part handling in relation to part geometry requirements, tools, accessibility to joints, positioning of tools, postural requirements as the factors for determining disassembly task difficulties. The method is developed for the application in the disassembly of medium size consumer products. It added on to the method by combining assemblability and disassemblability with maintenance tasks.

In [11] initial work developed a quantitative disassembly evaluation based on two parameters which were disassembly energy and disassembly entropy. Disassembly difficulty was determined through the physical energy required to release or disconnect a fastener or joint in which its behavior was determined by specific laws of mechanics such as torque for unscrewing against friction. Disassembly was also characterized by the number of interconnection and the direction of the disassembly operation. Their findings also indicated a direct correlation with the task time. The method only catered the unscrewing and unsnapping task with the attention towards electronic products.

The Hitachi Disassemblability Evaluation Method [12] is a patented method developed by Hitachi Corporation to evaluate the disassemblability of their electronic range of products. The method was developed based on experimental study of disassembly time and cost for various disassembly tasks. Based on the experiments, a disassemblability index was developed for the various standard operations. The index was based on three basic elements of movements which were upward movement, lateral movement and screw wise rotation. For each basic elements in a disassembly operation, a penalty score was given. Basic elements were multiplied by a supplementary element score if additional difficulties such as accessibility were found. Based on the total difficulty score, comparison of different design could

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be done.

[13] developed a model that determined disassembly difficulty based on assembly direction and type of joint used. The score for both of the assembly directions and joint were based on empirical analysis of motion time studies.

DFD method is among the commonly used method for disassembly evaluation [14] Development for this method was based information from various sources such as the WF method as well as experimental work. Basic elements of the disassembly operation were identified as time unit. Due to the prior work on design for assembly, this method used the reverse of the assembly as the basis for disassembly operation time, therefore additional time was added based on the following factors:

- Restriction of view
- Obstructed access
- Weight
- Physical obstruction
- Requirements for more than one person
- Requirements of mechanical assistance
- Requirements for special tools
- Distance to storage

[15] developed a disassemblability evaluation method for disassembling automotive parts. Based on the shapes of the product, a qualitative score was given for each process of disassembly such as fixing, finding joints, approach, disjoining, handling, etc. The scoring was done qualitatively by the user by assigning +ve, none or –ve on the influences of material type, work fixture, weight, contact point, gripping point, disassembly direction, surface roughness and product structure to the specific disassembly process.

In the Matsushita Assembly-Reverse Assembly method [16], the assembly and disassembly assessment are done simultaneously. The factors used for assessing disassemblability are material type, requirements for pre-processing, disassembly direction, component reusability and combination of type of joint. For several factors which were in direct relation to the assembly process, the scores were carried forward to the disassemblability evaluation such as unscrewing process, postural requirements, handling and fixture requirements which constitute reversal of the assembly process. The method is very limited in its type of disassembly operation tasks.

Using MTM model as a basis, [17] developed a disassemblability evaluation model by using the work factor approach. The disassembly task was broken down into work tasks. The work tasks were further broken down into task elements in which disassembly time was derived using the MTM model. The tasks covered preparation to disassembly processes such as identification and search elements to the final processing tasks.

[18] developed a different approach in disassemblability evaluation whereby components disassemblability viability depended on the value of the retrieve parts as either recycled material or reuse components. [19] also developed a model based on cost based on a multi-factorial approach. The difficulty of a disassembly process was attributed to the cost of running a disassembly facility. The method used expert opinions on determining the cost fractions.

[20] developed disassemblability evaluation model based on the experimental data. The main focus was to determine the removal time from various fasteners. Kondo's model attributed total disassembly time as the total amount of time to remove the fastener. Kondo also looked into the reassembly potential and the effect fastener age but did not include these parameters as part of the model. [21] developed a disassemblability model by using experimental data. The model known as UFI effort model looked specifically into the difficulties of unfastening fasteners. The model's fastener unfastening time was correlated to the fastener specific design parameters. The model's main intention was to look at the cost of disassembly for maintenance. [22] developed a model to optimize the selection of fastener based on artificial neural process. The model is a multi factorial model based on assembly, disassembly and product-in-use parameters. The information was developed based on the expert opinions data. [23] also develop a model for selection of fasteners. But their approach used the matrix method to determine the relationship between each part. The relationship depended on the product structure. This model concurrently looks at the assembly and disassemblability of the components and determines the appropriate fastener. [24] developed the disassembly model that was based on cost model to determine the fastener selection for maintenance and recycling. Apart from disassembly, reassembly and recycling cost the model also introduced failure probability of part and fastener cost due to fastener failure.

3. DISCUSSION

Based on the review of various design for disassemblability researches, several observations can be made. In general, the various developmental works in the design for disassemblability is often to relate disassembly task to cost. By determining the cost, the value of design for disassemblability changes

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will be tangible for the decision making process. Generally, three approaches can be observed, which are the process centric approach, geometry centric approach and fastener centric approach. The process centric approach mainly focuses on analyzing discrete tasks or activities in the separation process. While the geometry centric approach analyzes geometric shapes of parts that influence the separation process. The fastener centric approach on the other hand only focuses on the fastener in which views of removing the fastener are the primary contributors to the separation problems.

Current research trends are also seeing more concurrent evaluation approach being pursued, such as assembly-disassembly concurrent evaluation and disassembly-recylability concurrent evaluation. The design for disassemblability models can also be divided into three types of applications, which are the evaluative model, design guide model and optimization model. The evaluative model only analyses the impact of design on the disassembly difficulty. The design guide model is usually an extension of the evaluative model whereby hotspots are determined and generalized design guidelines are offered to reduce impact of hotspots. The optimization model on the other hand, optimizes the design parameter or assists in decision making in improving the design. Several design evaluation models have been established and some have great industrial success such as the Boothroyd Dewhurst, but it is observed that very few optimization models have been carried out for the design for disassemblability. Table 1 summarizes the classification of disassemblability models.

The tasks of a designer have been identified as the main cost contributor towards the product development process. The decision made during the early stage of product development or design process contributes towards 70-80 percent of the design cost. Making a wrong decision early in the design process could determine the success of a product later in its lifecycle. The tasks of balancing the various design issues rest on the designer's shoulders; and determining disassemblability for maintenance and end of life is are some issues that need decisive trade-off decision among other issues such as functional, assemblability and manufacturability issues. Designers are also faced with the difficult task of making a decision with such limited and often ambiguous information.

This is especially true during conceptualization where information is mostly estimates of actual condition. Current design for disassemblability method most often only provide means of assessing a design but the design changes are often left entirely to the designer's experience with limited design for disassembly guidelines. As most designer are not familiar with the area, then the task will be daunting especially due to the contradictive nature of the disassembly process towards a functional design. An optimization model that balances the disassemblability issues against functional and assemblability could reduce the decision making process of a designer in making design changes.

It could also avoid or overcome the design contradiction. Currently, only Gungor's and Jyh-Cheng &Yi-Ming's model attempts to tackle the problems above. But several short comings are observed. Gungor's model is based on qualitative information while Jyh-Cheng &Yi-Ming's model only covers a part of the relationship which is insufficient to make the trade-off decision. Both of the models only focus on the fastener selection. Unfortunately disassembly cost is not only attributed to just the fastener removal but also to the other tasks which could consume more time than the fastener removal.

It is also noticed that most of the designs for disassembly model require substantive amount of information in order to appropriately evaluate or optimize the design. Information such as a detailed understanding of the task required for disassembly or motions required to achieve tasks may not be available in the conceptual design. Most often, the current models concentrate their application during the embodiment stage where substantial definitive information is available. Changes made during the embodiment stage reduce the innovative opportunities that can be introduced in a product.

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Table 1: Approach of Different Models

	Process Centric	Geometry Centric	Fastener Centric
Evaluative	Desai et al Suga et al Kondo et al Hwa Cho Yi et al Villalba et al Kroll&Hanft Gungor-Gupta	Mok et al Boothroyd Dewhurst	Sodhi et al
Design Guide	Desai & Mital Shu & Flowers Desai Hitachi DEM Matsuhita		
Optimize			Gungor et al Jyh-Cheng & Yi-Ming

Furthermore, the parameters and language being used in most models are not reflective of engineering designer's terms. For example, in some models designers are required to define product's disassembly motion, disengage force or handling requirements which may not be easily identifiable during the conceptual design by designers. Designers are more familiar with parameters such as dimension, weight, surface friction or surface properties, joint strength etc which are related to design parameter that are identifiable during the conceptual design.

In summary, numerous studies have been conducted in developing the design for disassemblability models. Some have been proven to be effective and considered to be industry standards such as

Boothroyd Dewhurst method while others are still at the lab simulation phase as seen through the various simple lab case studies. None the less there still exist opportunities for further research. Limitations such as information/data requirement trade-off, designer based language, approach design for disassemblability at the concept design level design and parameter optimization issues are some of the noticeable elements that can be improved.

4. FRAMEWORK FOR METHODOLOGY DEVELOPMENT

From the review of the disassemblability models, two questions that will contribute to the improvement of design for disassemblability model arises.

Can a relationship be established between less a formed design specification data with a more defined disassembly parameter?

If a relationship can be establish, how can we use the established relationship to generate better concept designs that are functional wise and disassembly wise?

The answers to the research questions above can increase the designer's foresight towards disassembly problems during the conceptual design stage itself. This will allow more flexibility in the changes, hence more innovation opportunities regarding to the design for disassembly and the design for function trade-off will be available.

Based on the research questions above, a framework is proposed to specifically answer the questions. The framework attempts to add upon the existing knowledge in the design for disassemblability; several contributions are the functional design trade-off and parameter optimization to reduce disassembly time respectively. The framework model is a hybrid of geometric and fastener centric approach. Figure 1 below shows the proposed framework. The model considers part and fastener as complimenting objects. Each disassembly element consists of part disassembly and/or fastener removal. The user provides minimal information such as mating geometry, mating part material, part operating condition, aesthetic requirement, end of life option, maintenance requirement and joint strength. By using the information, the Analytical Heuristics Process approach will be used to determine the appropriate type of fastener for the element that has the minimum basic unfastening time. The unfastening time will be calculated based on the model by [25]. Workspace allowance and motion direction, although may be unnecessary during initial definition will also be factored in to determine the final unfastening time when such information is made available. In order to determine the part removal time information such as surface quality, material, weight and size should be direction, although may be unnecessary during initial definition will also be factored in to determine the final unfastening time when such information is made available. In order to determine the part removal time information such as surface quality, material, weight and size should be defined. Based on the information, the knowledgebase search algorithm by using Desai [9]model will determine the part removal time. The disassembly cost will be calculated based on unfastening and part removal time. This cost will later be an offset to generated revenues. If the element is not cost efficient in its disassembly, part feature hotspot can be identified by using the sensitivity analysis so that the parameter range can be broadened to allow more flexibility in improving disassembly efficiency.

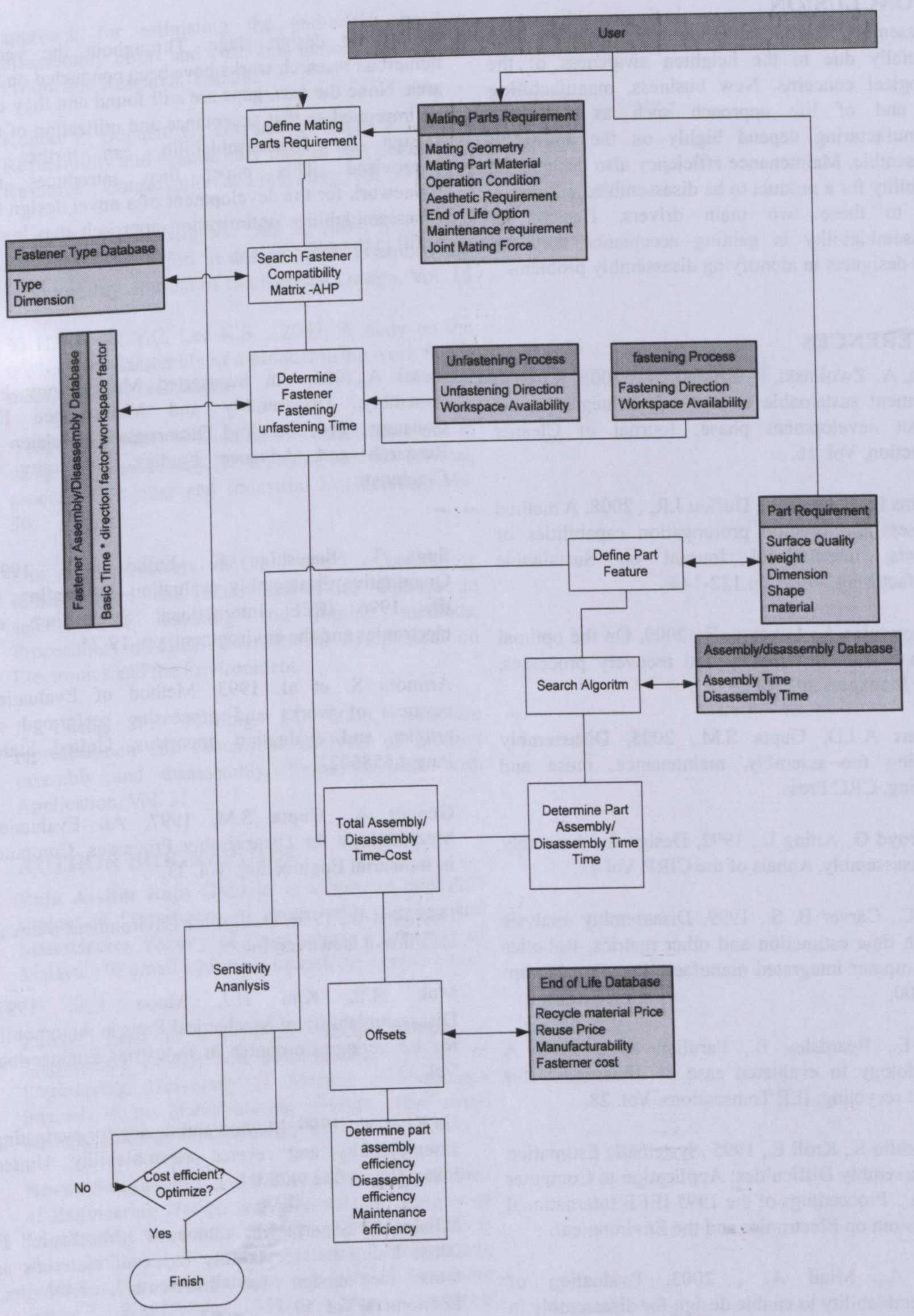

Figure 1: Disassembly Design optimization framework

5. CONCLUSION

Disassembly activities are gaining greater importance especially due to the heighten awareness of the ecological concerns. New business, manufacturing and end of life approach such as PSS and remanufacturing depend highly on the ability to disassemble. Maintenance efficiency also depends on the ability for a product to be disassembled efficiently. Due to these two main drivers, Design for Disassemblability is gaining acceptance that can assist designers in identifying disassembly problems during the design stage. Throughout the years, numerous research works have been conducted on the area. None the less, gaps are still found and they can be improved so that acceptance and utilization of the Design for Disassemblability can further be improvised. This paper then introduces the framework for the development of a novel design for Disassemblability optimization approach that hopes to fill in the gap.

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