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A Decision Support Tool for Product Design for Remanufacturing

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Abstract

The decision to include remanufacturing as part of product life cycle should be made as early as possible, as many barriers that occur during the remanufacturing process can be mitigated through proper product design at an early stage. The main objective of this research is to develop a Design for Remanufacturing and Remanufacturability Assessment (DRRA) tool to be used at early product definition stage. The design support tool will adopt the Fuzzy TOPSIS method to facilitate product design for remanufacturing from four major design perspectives, namely material selection, material joining methods, structure design and surface coating methods. Simplified Life Cycle Analysis methods have also been incorporated into the decision support tool to justify and improve the robustness of the design decision making. The utility of this tool is demonstrated using automotive parts design.

Keywords: Sustainable development; Remanufacturing; Design for Remanufacturing

1. Introduction

Remanufacturing has been recognized as a potential key enabler for sustainable production due to its effectiveness in closing the loop on material flow and extending product life cycle. It is the process of bringing products back to sound working status, through the operations of disassembly, sorting, inspection, cleaning, reconditioning, reassembly and testing [1]. Although there is potential benefit of remanufacturing, there are still many barriers in carrying out this EOL strategy, such as heavily damaged components, unavailability of remanufacturing equipment or technology, significant labor involved [2]. Many of these challenges can be addressed partially by careful product design at an early stage, as pointed out by several research groups; this has ignited the concept of Design for Remanufacturing (DfRem) as a much pursued design activity.

DfRem comprises a combination of design processes, such as design for disassembly, design for cleaning, of which the prioritization may vary depending on the process needed of the products [3]. In addition, DfRem should not be considered in an isolated manner. Given the potential conflict that DfRem may have with other DfX methodologies, such as assembly and manufacture, there is a need to evaluate the degree and impact DfRem has on the remanufacturing process as well as on other life cycle stages involved [4]. In this regard, a holistic Design for Remanufacturing and Remanufacturability Assessment (DRRA) tool has been proposed, which aims to steer a product design towards higher remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating methods. The tool employs Fuzzy Technique of ranking Preferences by Similarity to the Ideal Solution (Fuzzy TOPSIS) and Life Cycle Thinking to compare and evaluate design alternatives from both remanufacturing and life cycle perspectives, and thus to improve the effectiveness and robustness of decision making.

2. Literature review

The capacity to design a product for remanufacturing is often possessed by Original Equipment Manufacturers

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(OEMs) who have control over both the product design stage and remanufacturing stage. Not all the products are suitable for remanufacturing. There are certain qualities or properties that the product should possess before it can be considered for DfRem, such as high embedded value, long technology life-cycle or high durability. Detailed guidelines for identifying a candidate product or component for remanufacturing can be found from various existing remanufacturing literature [5-8].

The most commonly used and effective approach to facilitate product design for remanufacturing is through generating design guidelines to address the various barriers and challenges during the remanufacturing process. Existing design guidelines observed from various literature and research articles have presented a complementary but sometimes overlapping insight. In this regard, a detailed literature review on design guidelines for successful product remanufacturing has been conducted by Yang et al.[9]. The collated design guidelines have been presented in a generic manner and categorized according to the steps that constitute the remanufacturing process. Even though existing DfRem guidelines are fairly comprehensive, each remanufacturing aspect has to be considered individually when using such guidelines, which in reality, may be a daunting and time-consuming task for designers. In addition, many of the design guidelines are fairly general in description and consider rarely how these design guidelines may fit in with the already-sophisticated design process [10].

Besides design guidelines, another DfRem research focus is on formulating design tools and methods to address and alleviate the problems associated with the remanufacturing process. Some of these tools and methods are presented in the forms of mathematical models, software tools or statistics references, such as the remanufacturability matrix [11], and the remanufacturable product profile (RPP) [4]. Other DfRem tools are adapted from existing design approaches, such as Fuzzy-QFD for Remanufacturing [12], and the Failure Mode and Effects Analysis for remanufacturing [13]. However, one of the limitations of these DfRem tools are that many of them, especially those of quantitative nature, require too much technical data, and thus are either too complex to be used at an early design stage or can hardly make substantial changes to the design, as most of the product specifications have already been defined. Besides, life cycle thinking is often missing in these DfRem tools, which might cause sub-optimization of the design decisions. Thus, the motivation of this research is to address these challenges and limitations.

3. Methodology

In this section, a holistic decision support tool, namely DRRA, is presented. This approach will steer a product design towards higher remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating methods. To achieve this goal, design requirements will be categorized and presented according to these four aspects, and used as guidelines to assist the product design at an early stage. The impact of the generated design features will subsequently be evaluated from both the remanufacturing and holistic life cycle perspectives to make effective and robust design decisions.

3.1. Major DfRem considerations

Material selection is at the core of decision-making throughout product design development, as the material properties can influence various aspects of product life cycle, such as manufacturing cost, market acceptance, functional performance. Material characteristics play a key role in product remanufacturing performance. For example, an engine block may go through several remanufacturing processes during its entire life cycle, thus the selection of durable material, with high corrosion resistance, wear resistance and satisfying fatigue resistance, can increase the potential of engine block for remanufacturing substantially.

A critical design aspect that influences product fit, form and function is the material joining method. Typically, material joining involves utilizing various methods to affix two or more objects together, e.g., bolts, nuts, screws, rivets, staples, magnets, retaining rings, adhesive joints, welding, crimping, etc. It is an essential factor to be taken into account for EOL consideration, as the way the parts are joined together can facilitate or impede product disassembly for reuse, remanufacturing and recycling. Unplanned damage to the parts, especially the valuable ones, during the disassembly process is usually undesirable, as it may render the part or the whole product unusable. For example, an integrated snap-fit design may provide fast assembly and disassembly without introducing a different material, yet a failed snap-fit is difficult to salvage and prevents the part from reuse.

Another design aspect, namely product structure design, is closely related with product remanufacturing efficiency. Product remanufacturing, especially complex product remanufacturing, is a challenging task, as it involves disassembly process to separate different materials, and retrieve the reusable components in a non-destructive and cost-effective manner [14, 15]. Meanwhile, the number, design tolerance, shape and position of components will also affect the efficiency of various remanufacturing processes, e.g., cleaning, inspection, reconditioning, etc. For example, if a part to be replaced is located deep inside a product, accessing and retrieving the part becomes challenging, which makes remanufacturing expensive to be performed.

Surface coating is also a critical aspect that influences the potential of a product for remanufacturing. Usually, when a substrate material has been chosen for its bulk design characteristics, which contradicts the requirements for its surface design properties, surface coating will be applied to the substrate to meet those requirements, such as surface fatigue resistance, wear, corrosion, or aesthetic purpose. Improper selection of surface coating methods not only can increase the failure frequency of product caused by material wear or corrosion, but also add burden to product remanufacturing process substantially, e.g., a very smooth surface coating may involve substantial effort to be restored to a like-new condition, or a texture that is too coarse may trap dirt easily and complicate the cleaning process [16].

Table 1. Design consideration from remanufacturing perspective

	Material	**Material Joining Method**	**Structure Design**	**Functional and Decorative Surface Coating**
Durability	• Corrosion resistance • Wear resistance • Fatigue resistance	• Corrosion resistance		• Wear/ Corrosion/Surface fatigue resistance (Functional coating) • Fingerprint/Scratch Resistance (Decorative Coating) • Adhesion
Disassemblability and assemblability		• Disassembly without destruction, (include fastener/joint) • Disassembly without destruction, (exclude fastener/joint) • Disassembly, destruction allowed (for recycling) • Ease of reassembly	• Modularity for easy separation • Accessibility to valuable and reusable components	
Cleanability	• Ease of removing impurity and deposit • Resistance to cleaning		• Avoid intricate or unnecessary concealed design form	• Ease of removing the contaminants (coating removal is not required) • Potential damage to the substrate (coating removal is required)
Restorability/upgradability	• Ease of receiving machining process • Ease of receiving additive process • Ease of receiving conditioning process • Reliability of the reconditioned part		• Accessibility to the failure prone parts • Tolerance design for multiple life cycle • Modularity for replacement/upgradability	• Ease of receiving surfacing engineering
Environmental Health and Safety	• Recyclability • Air emissions and waste disposal • Toxicity • Scarcity of raw material • Law and regulation	• Compatibility with other parts • Toxicity		• Air emissions and waste disposal • Recyclability • Law and regulation
Cost	• Raw material cost	• Labor cost • Capital cost		• Labor cost • Material and energy consumption • Capital cost
Complexity	• No. of material	• No. of types of fastener/joint • No. of fastener/joint • Tool standardization • Accessibility to fastener/joint	• No. of parts and components • Standardization of parts and components	

The design considerations with respect to these four aspects are compiled based on the principles and guidelines of DfRem and presented in table 1.

3.2. Evaluating the Impact of DfRem on Remanufacturing

The proposed design considerations can be used as guidelines to assist product design at an early stage, or as a set of criteria for evaluating the impact of alternative design features on product remanufacturability. Selecting optimal design solutions based on the predetermined number of criteria as shown in table 1, is a multi-criteria decision making (MCDM) problem. Among the MCDM methods, Fuzzy TOPSIS is chosen in this methodology due to its simplicity and effectiveness. This algorithm is proposed by Yoon and Hwang [17] based on the idea that the best alternative should have the shortest distance from an ideal solution and farthest from the non-ideal solution. Basically, there are three main steps involved in this evaluation process:

a) Define the evaluating criteria and feasible design alternatives;
b) Determine the relevant importance of the criteria and the impact of the alternatives of those criteria;
c) Calculate the ranking of the alternatives using the TOPSIS algorithm.

To address the vagueness and uncertainty involved in the decision-making processes, the TOPSIS algorithm will be combined with the fuzzy sets theory to assess the alternative design options. Details of the algorithm of Fuzzy TOPSIS can be found in the previous research work [18, 19]. The output of this evaluation process will be a preferential ranking of the design alternatives with respect to their remanufacturing performance.

3.3. Evaluating the Impact of DfRem on Product Life Cycle

Product design for remanufacturing cannot be viewed in an isolated manner [7, 20] as it is often in conflict with other DfX methodologies. To improve the robustness and comprehensiveness of DfRem improvement, an evaluation scheme that can assess the impact of remanufacturability enhancement features in the overall product life cycle is required. Further, as remanufacturing has great potential to extend the number of product life cycle from one to multiple, the resulted complex product life cycle needs to be modeled properly, so as to support the decision making on improving product design and EOL recovery system.

In this regard, the traditional "cradle-to-grave" product life cycle has been adapted to "cradle-to-cradle", as graphically represented in figure 1. Due to the limited information on product or process during early design stage, a simplified LCA tool, namely Cumulative Energy Demand (CED) Method will be modified and adopted in this methodology to estimate the environmental impact of the design alternatives. It is an evaluation scheme that accounts for energy demand throughout the life cycle of a product. To apply CED to a complex product life cycle, six generic phases, namely material extraction and processing (MEP), manufacturing (MA), transportation (TR), usage stage (US), product take back (PTB), and remanufacturing (RE), will be included. The assessment framework will assume that the number of products circulated within a system is N, and during the remanufacturing stage, $\mu * N$ cores will be reprocessed to "good as new" quality to enter into next life-cycle, while the lost cores will be made up with $(1-\mu)*N$ virgin products.

CED will be utilized to represent the sum of the primary energy demand throughout the life span of a product. It is calculated as a function of the number of use cycles M, the successful remanufacturing rate μ, the primary energy demand for material extraction and processing CED_{MEP}, manufacturing CED_{MA}, transportation CED_{TR}, usage CED_{US}, product take back CED_{PTB}, and remanufacturing CED_{RE} of the product, as shown in equation 1. The value obtained for CED can be used to approximate the environmental performance of different design alternatives.

$$CED_{Total} = CED_{MEP_1} + CED_{MA_1} + \sum_{i=1}^{M} \left(CED_{US_i} + CED_{TR_i} + CED_{PTB_i} \right) + \sum_{i=2}^{M} \left(\mu_i * CED_{RE_i} + (1-\mu_i) * \left(CED_{MA_i} + CED_{MEP_i} \right) \right) \quad (1)$$

where:

M : number of life-cycles;
μ : successful remanufacturing rate;
i : i^{th} life cycle;
CED_{Total} : CED throughout the entire product life span.

CED_{MEP_i}, CED_{MA_i}, CED_{TR_i}, CED_{US_i}, CED_{PTB_i}, CED_{RE_i} : are CED for the material extraction and processing stage, the manufacturing process, the transportation stage, the usage stage, the product take-back stage, the remanufacturing process respectively during i^{th} life cycle.

The detailed implementation of this methodology can be found in Yang et al. [21]. Similarly, this concept can be used for economic cost analysis, namely Total Cost Analysis (TCA), to approximate the sum of the expense throughout the life span of a product. The output of the method will be the economic performance of different design alternatives, based on the value of successful remanufacturing rate and the number of life cycles that decision makers have assumed.

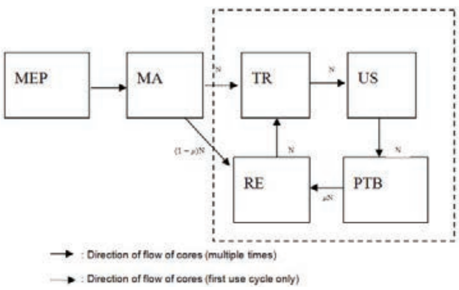

Fig. 1. Flow of products over multiple life-cycles

3.4. Overall approach for product design for remanufacturing

The DRRA tool is built based on the following four steps, which are illustrated graphically in figure 2.

Step 1: select the feature or aspects to be improved to facilitate remanufacturing, follow the list of remanufacturing design considerations and generate the feasible design alternatives.

Step 2: adopt the Fuzzy TOPSIS method to evaluate and compare the impact of the design alternatives on the remanufacturing process.

Step 3: evaluate the life cycle performance of the design alternatives using the proposed CED and TCA method.

Step 4: synthesize the results from step 2 and step 3 and make design decisions accordingly.

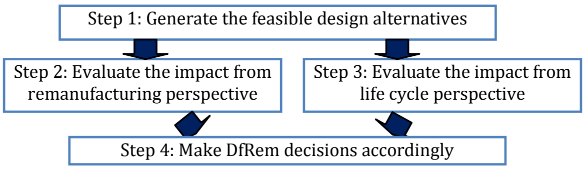

Fig.2. Flowchart for the proposed DfRem approach

4. Case study

The proposed DfRem support tool comprises four major design aspects, namely material selection, material joining methods, structure design and surface coating methods. To demonstrate its applicability, the aspect of material selection is illustrated here using alternators with three different design concepts. The parts which feature the difference in three alternator design are shown in table 2 [22].

To evaluate their impact on the remanufacturing process, three design alternatives are assessed using the material evaluation criteria proposed in this framework. The performance rating of the three types of alternators, as shown in table 3, will be used as the input for calculating the performance ranking of the design concepts, using the proposed DRRA tool (Step 2).

To further evaluate their life cycle environmental performance, the design information as well as the estimated functional and EOL performance of the three design alternatives, as shown in table 2 and table 4 [22], will be keyed into the proposed decision support tool. The parameters for energy intensity, such as embodied energy intensity, manufacturing energy intensity, remanufacturing energy intensity are stored in the database, which would automate and speed up the calculation process (Step 3).

5. Results and discussion

Table 5 shows the remanufacturing performance ranking of the three design alternatives. Design#I is ranked as the best candidate from the remanufacturing perspective, due to its desirable performance on durability, cleanability and restorability, and hence is much easier to be remanufactured into 'good as new' condition. In comparison, as the plastic-based components are more fragile and prone to wear, this has made design#II and design#III less advantageous for remanufacturing. However, if the life cycle perspective is considered, design#III has demonstrated its environmental benefit due to less energy consumed during the usage stage throughout the three life cycles, as shown in table 6.

Table 2. Specifications of three different alternator design

	 Design# I		 Design #II		 Design# III	
Component	Material	Mass (kg)	Material	Mass (kg)	Material	Mass (kg)
Belt fitting	Steel	0.52	Steel	0.52	Aluminum	0.18
Fan	Steel	0.14	Plastic/PP	0.02	Plastic/PP	0.02
Bearings	Rolled steel	0.10	Rolled steel	0.10	Plastic/PP	0.01
Housing	Iron cast	2.53	Aluminum	0.96	Aluminum	0.96

Table 3. Design candidates and their performance ratings

CRITERIA	Importance	Design #I	Design #II	Design #III
Durability	High	Good	Medium good	Fair
Cleanability	High	Good	Medium good	Fair
Restorability	Very high	Good	Medium good	Fair
EHS	Medium	Good	Medium good	Fair
Cost	Low	Fair	Medium good	Good
Complexity	Low	Medium good	Fair	Fair

Table 4. Functional and EOL performance of design alternatives

	Design #I	**Design #II**	**Design #III**
Life mileage (mile)	125,000	125,000	125,000
Functional performance	Equivalent	Equivalent	Equivalent
Belt fitting reman rate (%)	90%	90%	25%
Fan reman rate (%)	90%	0%	0%
Bearings reman rate (%)	50%	50%	0%
Housing reman rate (%)	85%	60%	60%

Table 5. Closeness and ranking of each design candidates

	Relative closeness	Ranking
Design I	0.91	1
Design II	0.49	2
Design III	0.09	3

Table 6. Relative energy consumption of design#II and design#III to design#I

	1st life cycle	2nd life cycle	3rd life cycle
Design II	-4.29 GJ	-12.19 GJ	-20.09 GJ
Design III	-6.48 GJ	-15.20 GJ	-23.91 GJ

A comparison of the results has addressed the importance of taking life cycle perspective into considerations, while designing products for remanufacturing. Even though design#III, featured with light weight material, performs poorly during the remanufacturing process and requires more raw materials for making up the non-reusable parts, this disadvantage can be mitigated by its weight induced energy saving during the usage stage. Moreover, sensitivity analysis has shown that whether the light weight design strategy is beneficial depends heavily on whether the weight induced energy saving during the use phase is sufficient to compensate for the potentially increased environmental impact of producing this part at the production stage as well as the remanufacturing stage. For example, if the weight-induced fuel saving rate decreases by 50%, design#I will outperform the rest of the design alternatives from the life cycle perspectives.

A computation tool has been developed, which allows for fast computation and ease of use of this design methodology. With this tool, decision-makers can obtain the impact of remanufacturing design features on both remanufacturing performance as well as the overall product life cycle, so as to improve the effectiveness and robustness of decision making and encourage greater incorporation of the remanufacturability concept during the product design stage. Meanwhile, the capacity to automate the evaluation process, especially building the database which is capable of assigning the performance rating automatically to different design alternatives is under development.

Beside material selection, the proposed decision tool can assist and steer a product design towards higher remanufacturability from the perspectives of material joining methods, structure design and surface coating methods. While these four aspects are only a subset of product design considerations, they were selected because they are fundamental to the realization of remanufacturing. Other design considerations, such as labeling design and recycling considerations, will be accounted in the next stage of the research work. Moreover, recognizing the impact of design on EOL possibility, the research topic of DfRem has received a lot of attention in recent years. Factors that may affect the integration and implementation of DfRem, such as management support, cross functional communication, market demand, shall be investigated [23].

6. Conclusion

With the increasing attention that the remanufacturing industry has received, the concept of DfRem has been accepted during the product design and development stage. To facilitate the DfRem implementation, a holistic decision support tool, namely DRRA, is proposed in this paper to steer a product design towards higher remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating methods. The impact of remanufacturability enhancement design features on both remanufacturing performance and overall product life cycle performance can be examined using the Fuzzy TOPSIS methodology and CED/TCA respectively, so as to achieve a robustness and comprehensiveness of the remanufacturing design decisions.

The main contribution of this research is the compilation of the design features that are relevant to remanufacturing performance and the formulation of a systematic design tool for evaluating the design alternatives in a comprehensive and holistic manner. The tool can be adopted in the early design stage as only the relative remanufacturing performance ranking is required as input for remanufacturing impact analysis. Meanwhile, the life cycle thinking is incorporated in the evaluation scheme, which further improves the effectiveness and robustness of DfRem decision making.

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