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Design for Disassembly for Remanufacturing: Methodology and Technology

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Abstract

Remanufacturing has become a major aspect of life cycle engineering. Methodologies have been proposed on the optimal ways to disassemble a product in terms of sequence planning and hierarchical modular modelling. New technologies, e.g., the use of smart materials, have enabled fasteners to be removed simultaneously, improving the disassembly efficiency. This paper reviews the advantages, limitations and applications of these methodologies and technologies which can be incorporated at the beginning of the product design stage to facilitate disassembly. A conceptual framework will be discussed to illustrate the integration of methodology, technology and human factors to further enhance the disassembly process.

Keywords: Remanufacturing; Disassembly; High value cores

1. Introduction

1.1. Remanufacturing

With an emphasis on environmental sustainability, remanufacturing has become a major aspect of life cycle engineering. Remanufacturing brings used products back to equal or better than new condition [1]. The primary benefits arise from the reuse of resources. In contrast to recycling, remanufacturing retains the geometric shape of the parts hence eliminate or minimize the need for the material forming process, resulting in a reduction of carbon footprint [2].

Remanufacturing processes usually require disassembly of a product in order to retrieve the cores for refurbishments, which may incur higher cost. However, the cost to produce a remanufactured unit of a particular product is generally lower than the cost to produce a new unit because of the savings in raw materials, energy, and manufacturing plant and equipment in the remanufacturing process [3].

1.2. Disassembly for remanufacturing

Disassembly is an inevitable process in order to retrieve high value cores within a product for remanufacturing. A survey [2] conducted shows that besides parts availability, disassembly is a concern for remanufacturing. Almost all disassembly for remanufacture is manual [4]. This could be due to a number of reasons. For example, high capital cost is required for automation. Flexibility is also lost as automated disassembly line may not be able to cater to the different kinds of product infrastructure and design for remanufacturing [5]. Circumstances like corroded parts will still require human intervention to determine the appropriate tools for the removal of the affected fasteners. However, disassembling a product manually may not be cost effective due to the inefficient

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disassembly design for many products [5], which increases the time to disassemble resulting in higher labour cost.

Products that are designed for disassembly and remanufacturing can deliver much greater savings than can be achieved through remanufacturing of a product that is not designed with this intention [6]. Therefore, in the context of design for disassembly (DfD) for remanufacturing, the fundamental requirements are:

- Simplify joining method for quick disassembly
- Prioritize retrieval of cores over non-remanufacturable parts
- Protection of core to maintain part's integrity
- Incorporate DfD as early as possible in the product design stage in order to facilitate disassembly processes

DfD Guidelines	Justification
Minimize number of fasteners	Most disassembly time is spent on fastener removal
Minimize the number of fasteners removal tools required	Changing tools costs time
Fasteners should be easy to remove	Saves time during disassembly
Fastening points should be easy to access	Awkward movements slow down disassembly process

Fig 1: Design for disassembly guidelines [7]

DfD guidelines have been provided to serve as a basis for designers to incorporate an easy-to-disassemble mindset during product design. Figure 1 shows a few DfD guidelines from the ergonomic perspective. These rules enable the designers to have a good reference, although they may not be applied extensively during the design stage.

Various disassembly methodologies have been proposed by academic researchers. Most of them are based on the hierarchical modular modeling which can be utilized for disassembly sequence planning. With the advancement of materials innovation, quick unfastening methods could be deployed.

Design for Disassembly should constitute three aspects (Figure 2), namely the adoption of suitable methodologies, implementation of technologies and incorporation of human factors (ergonomics) consideration, for an effective product dismantling process.

Human factors must be considered in the design of a product and the disassembly process due to the manual operations of disassembly. Avoidance of these factors creates various problems and reduces worker efficiency [8].

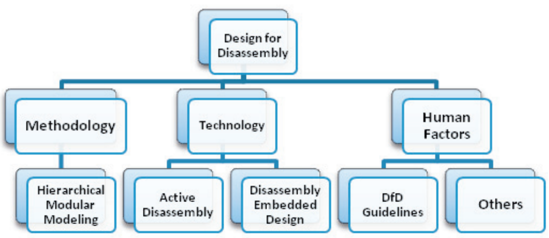

Fig 2: Three aspects of design for disassembly

2. DfD Methodologies

In many cases, a product can be disassembled into a number of subassemblies, and from the subassemblies, into various parts and components. Each of the subassemblies can be considered a module, forming a hierarchical product tree (Figure 3). There are many studies and literatures to date which discuss the development of design aids, such as tools and methods, to alleviate the problems encountered in disassembly. These usually come in the form of mathematical models [9].

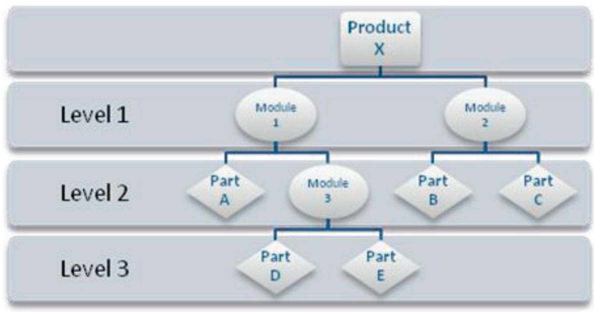

Fig 3: Hierarchical modular modeling of a product

The And/Or graph representation [10] and the Petri-Net [11] are some of the models that have been proposed to establish the relationships between the subassemblies and components, and the possible routes to disassemble a product into individual parts. The And/Or graph representation (Figure 4) is based on the ability to find all the stable subassemblies and all the physically feasible decompositions of an assembly, which can be obtained by analyzing its corresponding connection graph. The Petri-Net approach is able to model a disassembly process and system resources simultaneously [12]. It can be used for products containing complex And/Or disassembly precedence relationships [11].

These mathematical models, based on hierarchical modular modeling, are used to determine an optimal disassembly sequence based on the shortest route to reach a core and the geometric constraints of the product. Disassembly sequence planning aims at generating feasible disassembly sequences for a given assembly, where the feasibility of a disassembly sequence is checked by the existence of collision-free motions to disassemble each component or subassembly in the sequence [13]. This provides core protection without unnecessary damages in order to maintain its integrity.

A disassembly sequence can be generated using interactive or automated approaches. The interactive method mainly focuses on each designer's query on the connection between a pair of parts or the feasibility of a single disassembly operation. The automated approach utilizes the CAD model of an assembly to determine the geometry of the parts and their interaction [14].

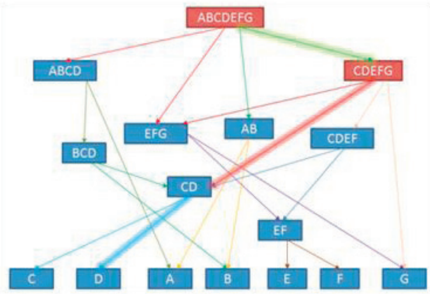

Fig 4: AND/OR disassembly representation. Red assembly represents OR node with dual AND output

2.1. Selective Disassembly

The objective of selective disassembly is to remove selected parts [15]. Pertaining to remanufacturing, the selected parts are the remanufacturable cores. Selective disassembly can be used to prioritize the retrieval of remanufacturable cores. In most products, a selected part can be disassembled from two or more different directions [13]. Each route taken can have different disassembly outcome. An optimal disassembly sequence therefore is required to determine the shortest possible route to reach the core. As far as remanufacturing is concerned, prioritizing the retrieval of high value cores over other non-remanufacturable parts within a product is essential to ensure a cost effective disassembly process. Not all parts are required to be dismantled. Disassembling non-remanufacturable parts which will be scrapped eventually impedes the remanufacturing process. With reference to Figure 4, if Part D is the core to be remanufactured, the preferred disassembly sequence to follow would be the highlighted route, which is the shortest path to reach Part D.

2.2. Advantages and Limitations

Establishing a hierarchical modular model provides a systematic approach for the designer to determine an optimal sequence to retrieve desirable cores for remanufacturing. In addition, prioritizing the retrieval of core and core protection are possible through selective disassembly. It is suitable for products of modular design.

However, modularity requires maintaining independence between components and processes in different modules, encouraging similarity in the components and processes in a module, and maintaining interchangeability between modules [16]. Therefore, the hierarchical modular modeling approach would not be applicable to products with many parts interaction, such as interference fit. A suitable methodology may become difficult to be established when considering an assembly consisting of many levels. In addition, the methodology does not address the practical problems faced during disassembly, such as space limitation and tools accessibility.

3. DfD Technologies

Generally, parts and components can only be separated after one or more disassembly actions. This may involve loosening one fastener at a time with a single disassembly action. For instance, removing the bolts from the casing of an alternator only disassembles the component partially. There are other fasteners that need to be removed in order to disassemble the alternator completely. This is described as one-to-one disassembly [17]. A joining technique that can make the disassembly process simpler and quicker, enable the core to be removed before crushing and shredding should be considered and used [18].

A one-to-many disassembly corresponds to the disassembling of a number of fasteners of a product simultaneously. This can be achieved by incorporating disassembly embedded design into the product or the use of fasteners made from smart materials for active disassembly. The advantage of one-to-many disassembly is the removal of not just one but multiple fasteners under the influence of external stimuli, such as heat, chemical, etc., thus increasing the efficiency for disassembly [5]. The difference between disassembly embedded design and active disassembly is that the latter can be incorporated in any design without extensive planning [17].

3.1. Disassembly Embedded Design

Disassembly embedded design incorporates a disassembly mechanism that is being designed to be integrated within a product. The mechanism could be 'activated' mechanically, thermally, electrically or under the influence of electromagnetism to initiate the disassembly process [5].

For instance, snap fit connections can be embedded within the product with a centralized actuation element that is able to trigger the snap fits to dislodge from their locked positions. In this case, a mechanical force can be applied at the actuation port to activate the disassembly process [19].

3.2. Active Disassembly

Active disassembly (AD) is a process whereby a product makes use of external triggering factors, e.g., temperature, magnetic force or pressure, for the release of fasteners. Active disassembly includes employing smart materials, freezing elements, soluble elements, pneumo-elements and hydrogen storage alloy elements as a fastening technique [5].

Active disassembly using smart materials (ADSM) is by far the most researched area within the AD realm [17]. Smart materials, such as Shape Memory Alloys (SMA) and Shape Memory Polymers (SMP), are able to deform or experience a change in shape under the influence of an external stimulus. Due to their unique shape memory properties, fasteners made using smart materials can respond with a shape change when subject to the triggering mechanism. The change in shape allows disengagement of parts easily. Generally, AD can be applied to various forms of products. It is considered as generic for certain functional requirements [5].

For SMA, the phase transformation of the material from austenite to martensite and vice versa is responsible for the reversible memory effect within the material itself. The external stimulus for SMA is primarily the transformation temperature pertaining to their phase change.

The inherent glass transition temperature (Tg) of polymers is the shape memory mechanism for SMP. Below the Tg, the SMP becomes rigid while above its Tg, it becomes more elastic and flexible, allowing the fasteners to be removed easily.

3.3. Advantages and Limitations

Disassembly embedded design is a product-specific application. Product designers have to make a conscious effort to integrate the disassembly mechanism into the product structure itself. Due to space and manufacturability constraints, Disassembly embedded product design can become complicated.

The major advantage of using smart materials is its ability to release multiple fasteners under a single trigger mechanism to increase the efficiency of the disassembly process as more often, the bulk of the disassembly time is spent removing fasteners. As a result, human effort in removing (i.e., unfastening) the fasteners can be eliminated or reduced. For example, a study was conducted to disassemble an automotive instrument panel to compare the efficiency of ADSM disassembly and conventional disassembly. The result shows that ADSM has a percentage time saving of 55% [20]. In addition, since the fasteners can be released or loosened without the use of mechanical tools, thus fasteners accessibility is no longer an issue. A triggering factor, such as the activating temperature, will be required by the remanufacturers. Facilities and tools to activate the trigger are also necessary. As SMA remains a niche material used largely in the aerospace and biomedical applications, the cost is still relatively higher than the conventional fasteners made from stainless steel. Materials, such as NiTi, is difficult to fabricate with conventional machining as it causes significant tool wear [21].

Accidental triggering is a concern especially for SMP considering that the polymer's glass transition temperature is relatively low [22]. The service temperature of the components in the vicinity of the smart materials being used needs to be taken into consideration to prevent unintentional triggering of active disassembly. Fabrication of shape setting alloy requires additional training process to set the materials in the desired shape.

4. Discussion

Figure 5 presents an overview of the advantages and limitations for both the methodologies and technologies discussed. The methodologies and technologies can complement one another.

Based on the advantages and limitations of the discussed methodologies and technologies, each has the capability to fulfil the requirements for design for disassembly for remanufacturing as mentioned in Section 1.2.

However, not all the requirements can be satisfied if either methodology or technology is used alone (Figure 6). Utilization of both methodology and technology concurrently will improve the efficiency for the disassembly process for remanufacturing.

	Advantages	Limitations
Methodology	Systematic sequence planning	Do not address practical problem faced during disassembly (i.e. fasteners accessibility, interference fit, adhesive joints, welded parts etc.)
	Prioritisation of high value cores through selective disassembly possible	
	modular model allows simultaneous disassembly work on smaller sub-assemblies	
Technology	Address practical problem faced during disassembly i.e. fasteners accessibility	May complicate design consideration
		Knowledge of the shortest possible route to reach high value cores required

Fig 5: Advantages and limitations

		Methodology	Technology
Requirements	Simplify joining methods for quick disassembly		✓
	Prioritize retrieval of cores	✓	
	Protection of cores	✓	
	Incorporate in early design stage	✓	✓

Fig 6: Each aspect contributes differently to design for disassembly

5. Conceptual Framework

As mentioned earlier, disassembly is a very labour intensive process. In addition, an automated disassembly line may not be feasible to cater to different kinds of product infrastructures and design for remanufacturing. Certain circumstances will still require human intervention to determine the appropriate tools and methods for the removal of the affected fasteners. In such a human-oriented situation, human factors and the ergonomics aspect of the disassembly process should not be neglected.

Figure 7 shows the proposed three-pronged strategy for design for disassembly which serves to leverage the benefits each of the approach can bring to compensate their limitations. The first prong of the strategy acknowledges the need for a systematic disassembly sequence planning in order for a productive workflow.

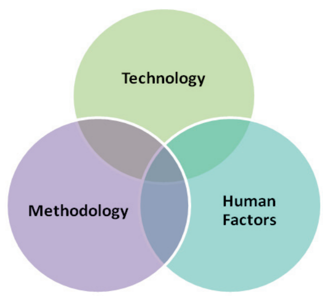

Fig 7: Three-pronged approach for design for disassembly

Technology, which serves as the second prong, recognizes the benefit it can bring by having a method for one-to-many disassembly. The third prong articulates the importance of human factors involved in manual disassembly. The three prongs will make up the entire framework for an efficient and effective disassembly process.

An example based on the automobile remanufacturing industry is used to illustrate the three-prong approach for design for disassembly. The implementation of the End of Life Vehicle Directives has placed enforcement for remanufacturers to attain the goal of vehicles reusability and/or recyclability of at least 85% and reusability and/or recoverability of at least 95% by weights [23]. In addition, the automobile has the longest tradition of remanufacturing and accounts for 2/3 of the global remanufacturing activities in terms of volume [24]. The vast majority of the firms that make up the remanufacturing industry are third-party companies which do not manufacture original products [1]. In addition, disassembling an automotive part, such as an engine, may be a more challenging task as compared to that of an electronic product due to the service conditions they are subject to. For instance, fasteners of an engine are more likely to corrode compared to fasteners of an electronic product. Removing a corroded fastener of an engine may require appropriate special tooling or technique ascertained by a skilled worker. Decision making is involved. Thus, the three-pronged approach is relevant to the automotive industry.

In this case study, the proposed three-pronged strategy is used to integrate methodology, technology as well as human factors to maximize their benefits. Their advantages serve to compensate their limitations which could further enhance the disassembly process.

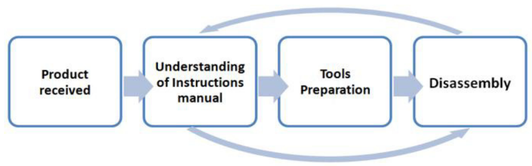

Fig 8: A typical disassembly process for remanufacturing

A typical disassembly process is as shown in Figure 8, which begins with the receiving of the product, followed by the understanding of the instruction manual to determine the types of tools to be used before the actual disassembly process commences. In certain circumstances, cleaning (e.g., de-greasing) may be required to access the fasteners. Many times, the disassembly process is not linear. An operator needs to refer to the instructions manual to further understand the disassembly process. Using the retrieval of a car engine as an example, the incorporation of the three-prong approach will be able to increase the efficiency of the disassembly process.

5.1. Incorporation of Methodology

A systematic disassembly sequence is needed for complex disassembly tasks, such as the removal of the engine from the bonnet of the car. The incorporation of an approach in the form of an optimal disassembly sequence derived from a methodology, i.e., the And/Or graph representation will provide tremendous aid for the operator. There can be more than one disassembly route to reach the engine. In order to attain it at the shortest possible time, an optimal disassembly sequence is required. A feasible disassembly sequence can be generated to determine a collision-free motion that is able to disassemble the engine and protect the core. The optimal disassembly sequence can easily be captured in the instructions manual of the engine. The duration to remove the engine will also be reduced. However, an operator may still face with practical issues such as accessibility of fasteners and corroded parts which inhibit standard operational practice.

5.2. Incorporation of Technology

The complexity of an assembly may prevent the operator from reaching the desired fasteners within a limited space constraint. Some of the fasteners will be difficult to reach with the tools. The space constraint may hinder any further disassembly actions. Incorporating ADSM will be able to relieve any difficult situations. Fasteners can be released under the influence of an external trigger simultaneously thus reducing the disassembly time. Practical constraints, such as fasteners accessibility will be eliminated. ADSM application has been implemented in the automobile industry. Chevrolet has employed smart materials for its new Corvette Stingray. The technology makes use of a shape memory alloy wire that opens the hatch vent whenever the deck lid is opened in the rear of the car. Basically, heat from an electrical current activates the small wire, which moves a lever arm to open the vent, allowing the trunk lid to close. Once closed, the current switches off, and the shape memory wire returns to its original shape [25]. ADSM has substantial potential to be used in the automobile industry for future applications pertaining to design for disassembly. For instance, smart materials can be used for fastening devices which are difficult to access in the process of retrieving the engine.

5.3. Considering Human Factors

Disassembly is a manual process. The performance of the human operators depends to a large extent on their understanding of the instructions [26]. The experience of the operator may not be sufficient to deal with a variety of products from different OEMs. In addition, disassembly is not a straightforward process. As such, operators sometimes need to make decisions *in situ*. For example, when met with difficulties during disassembly, one may improvise a flat head screw driver to knock a part out from interference fit which may inevitably cause undesirable scratches, and damaging the core. During the disassembly of the engine, the operator might be put in an awkward position in order to reach the engine which will impede the disassembly process. These human associated behaviours have to be taken into consideration in order to ensure an effective remanufacturing process. An ergonomic factor that can be incorporated into this example is to use colored markers/identifiers to indicate the necessary fasteners that are required to be removed in order to retrieve the engine. This will enable the operator to remove the fasteners in an intuitive manner without having to refer to the instructions manual constantly. Safety indicators can also be specified on the component itself using decals. Additional time will be saved.

6. Conclusion

Each of the aspects of design for disassembly discussed can enhance the disassembly process. However, they contribute in different manners. The synergy of methodology, technology and human factors serves to bring about a greater impact by integrating their benefits to make design for disassembly more efficient and complete. The above example has illustrated this proposed framework. All of the aspects can be incorporated at the initial product design stage. Future work will involve identifying a suitable method to generate an optimal disassembly sequence for a product, appropriate technologies that can be incorporated, as well as a methodology to consider the ergonomics factors in the disassembly process and sequence.

7. Acknowledgements

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