A DESIGN METHODOLOGY FOR REMANUFACTURING AND REMANUFACTURABILITY ASSESSMENT

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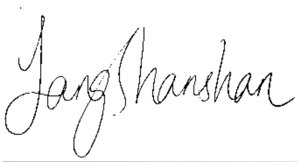
DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.



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SUMMARY

Remanufacturing is a key enabler for sustainable production due to its effectiveness in closing the loop on material flow, extending product life cycle and reducing production waste and emission. It is the process of returning an EOL product to 'as-new' condition, through the processes of disassembling, cleaning, inspecting, reconditioning, replacing and reassembling the components of a part or product and thus provides a material recirculation loop within the product system. This thesis presents decision support tools, to be used at early design stage, to analyze the feasibility of a product and its components for remanufacturing, and to facilitate the design of the product for remanufacturing. Meanwhile, the research work proposes a comprehensive approach, to be used at product End of Life (EOL) stage, to generate optimized recover plans for the returned products.

The decision to include remanufacturing as a part of product life cycle should be made early at the design stage, as about 80% of the cost of the product are determined at this stage (David et al., 2014). However, this decision involves rather complex considerations, as business, engineering, market, economic and environmental factors can all affect the success of a remanufacturing endeavor. Besides, the uncertainties involved in various dimensions, such as quality, quantities and timing of product return, have further complicated the remanufacturing strategy planning issue. In this regard, the proposed research will explore a logical way of determining whether certain products or components are feasible for remanufacturing at the initial product design stage, through weighting and analyzing a comprehensive list of decision making factors. Genetic Algorithm will be adopted to determine a Pareto set of optimal EOL strategies, which will facilitate the effort of decision makers to maximize the environmental benefit of remanufacturing for a given economic profit.

Meanwhile, the research work has also adopted a proactive approach to improve the remanufacturability of the products/components, namely design for remanufacturing. As pointed out by various studies, the barriers to the remanufacturing process can largely be traced back to the initial product design stage and this has highlighted the importance of early integration of the design characteristics that can enhance the product or process remanufacturing efficiency. The research work aims to steer a product design towards remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating during product design stage. And the generated design alternatives will further be evaluated and compared from both remanufacturing and life cycle perspectives, through multi-criteria decision making technique and life cycle assessment method respectively, to improve the effectiveness and robustness of the design decisions.

Besides early design stage, the research work has also examined the suitability of the products and especially its components for remanufacture or to be discarded during the EOL return stage based on their return conditions. The framework includes both qualitative and quantitative analyses to address the operational and technological considerations for product remanufacturing and optimize the environmental and economic performance. Probability theory is utilized in the proposed framework to analyze the impact of the quality of the returned products on EOL decision making. In addition, to represent the product structure hierarchy and the interconnections among the components of a product, the Hierarchical Attributed Liaison Graph (HALG) is used, allowing both complete and partial disassembly strategies to be considered during EOL strategy planning.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
CC	Cumulated Cost
CED	Cumulated Energy Demand
CGI	Compacted Graphite Iron
DfA	Design for Assembly
DfE	Design for Environment
DfRem	Design for Remanufacturing
DfX	Design for X
DRRA	Design for Remanufacturing and Remanufacturability Assessment
EHS	Environmental Health and Safety
ELECTRE	Elimination and Choice Expressing the Reality
EOL	End of Life
HALG	Hierarchical Attributed Liaison Graph
IR	Independent Remanufacturers
LCA	Life Cycle Analysis
MCDM	Multi-Criteria Decision Making
MA	Manufacturing
MEP	Material Extraction and Processing
NSGA	Non-Dominated Sorting Generic Algorithm
OEM	Original Equipment Manufacturers
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PSS	Product Service Systems

PTB	Product Take Back
QFD	Quality Function Deployment
RE	Remanufacturing
RFID	Radio Frequency Identification
RoHS	Restriction of Hazardous Substances
SAMSG	Sustainable Automotive Materials Selection Guide
TOPSIS	Technique Of ranking Preferences by Similarity to the Ideal Solution
TR	Transportation
RDMF	Remanufacturing Decision-Making Framework
SETAC	Society of Environmental Toxicology and Chemistry
VIKOR	Vlse Kriterijumska Optimizacija Kompromisno Resenje
WEEE	Waste Electrical and Electronic Equipment
US	Usage Stage

LIST OF SYMBOLS

Chapter 3

C_{Reman_i}	Remanufacturing cost of component i
$C_{Miscellaneous_i}$	Cost of handling, disassembly, storage, reassembly of component i
$C_{Shredding/Recycling_i}$	Shredding/recycling cost of component i
$C_{Newpart_i}$	Replacement cost of component i
$C_{Landfill_i}$	Landfill cost of component i
$E_{Material\ extraction_i}$	Energy required to extract the raw material to produce component i
$E_{Material\ process_i}$	Energy required to process the material to produce component i
$E_{Manufacturing_i}$	Energy required to manufacture component i
E_{Reman_i}	Energy required to remanufacture component i
$E_{Shredding/Recycling_i}$	Energy required to shred/recycle component i
RS	Product resale price
CC	Product collection cost
DS_i	Disassembly cost of assembly i
E_{total}	Energy required to produce the product
$X_1 \ldots X_m$	Design candidate
$A_1 \ldots A_n$	Evaluation Criteria
j	The number of the Criterion
n	Total Number of Criteria
α_j	Weight obtained via the entropy method

β_j	Subjective weight assigned by experts from the remanufacturing field
w_j	Weight for the *j*th criterion
i	The number of the alternative
m	Total number of alternatives
P_{ij}	The normalized performance matrix
r_{ij}	The performance rating of *i*th material alternative with respect to *j*th evaluation criterion
E_j	The entropy of the normalized values of *j*th criterion
α_j	The weight of the entropy of *j*th criterion
M	Number of life-cycles
μ	Successful remanufacturing rate
i	i^{th} life cycle
CED_{Total}	CED throughout the entire product life span
CC_{Total}	CC throughout the entire product life span
CED_{MEP_i}	CED for the material extraction and processing during i^{th} life cycle
CC_{MEP_i}	CC for the material extraction and processing during i^{th} life cycle
CED_{MA_i}	CED for the product manufacturing during i^{th} life cycle
CC_{MA_i}	CC for the product manufacturing during i^{th} life cycle
CED_{TR_i}	CED for the transportation of product during i^{th} life cycle
CC_{TR_i}	CC for the transportation of product during i^{th} life cycle
CED_{US_i}	CED for the use of product during i^{th} life cycle

CC_{US_i} CC for the use of product during ith life cycle

CED_{PTB_i} CED for the take-back of product during ith life cycle

CC_{PTB_i} CC for the take-back of product during ith life cycle

CED_{RE_i} CED for the product remanufacturing during ith life cycle

CC_{RE_i} CC for the product remanufacturing during ith life cycle

Chapter 4

q Quality level of the product/component

Pr_{ij} (q1|q2) Probability of the quality of its subcomponent i equals to q1, given the quality level q2 of assembly j

SA_{ij} Subassembly ij

$C_{i,j}$ Component $C_{i,j}$

$PF(C_{i+1,j}, q_{i+1,j})$ Profit of each component $C_{i+1,j}$ under quality level $q_{i+1,j}$

$PF(SA_{ij}, q_{ij})$ The expected profit for processing the subassembly SA_{ij} with quality level $q_{i,j}$

DC_{ij} Disassembly cost associated with subassembly SA_{ij}

ij The jth component on ith level

X_{ij} Indicator of the EOL strategy of component ij

X_{ij} =1, if the component ij is to be upgraded

X_{ij} =2, if the component ij is to be restored

X_{ij} =3, if the component ij is to be discarded with replacement

(EC_{ij}, X_{ij})	The economic index of component ij, if EOL option X_{ij} is taken
(PC_{ij}, X_{ij})	The cost of restoring or upgrading the component ij (if X_{ij}=1 or X_{ij}=2) or the cost of disposing the component ij (if X_{ij}=3) ($)
(NC_{ij}, X_{ij})	The cost of producing or ordering the new component ij when X_{ij} =3; otherwise (NC_{ij}, X_{ij})=0 ($)
(EV_{ij}, X_{ij})	The environmental index of component ij, if EOL option X_{ij} is taken
(RMR_{ij}, X_{ij})	Mass of raw material required for restoring or upgrading the component ij (if X_{ij}=1 or X_{ij}=2) or replacing with a new component ij (if X_{ij}=3) (kg)
RMC_{ij}	Raw material cost ($/kg)
(EP_{ij}, X_{ij})	Energy required for restoring or upgrading the component ij (if X_{ij}=1 or X_{ij}=2) or disposal and replacing with a new component ij (if X_{ij}=3) (MJ)
EC	Energy cost ($/MJ)
(WDP_{ij}, X_{ij})	Waste generated for restoring or upgrading component ij (if X_{ij} =1 or X_{ij}=2) or disposing the component ij and replacing with a new component (if X_{ij}=3) (kg)
WMC_{ij}	Waste management cost ($/kg)

(TOX_{ij}, X_{ij}) Toxic discharged during restoring or upgrading of component ij (if X_{ij} =1 or X_{ij} =2) or disposing the component ij and replacing with a new component (if X_{ij} =3) (kg)

WMC_{ij} Toxicity management cost ($/kg)

$PF(C_{ij}, X_{ij})$ The index of component ij, if EOL option X_{ij} is taken

1. INTRODUCTION

This introductory chapter describes the background of this research topic and briefly states the motivation that drives this research work. Further, the objectives as well as an overview of the dissertation are described.

1.1 Sustainable Production and Remanufacturing

Along with the rapid increase in living standard, the consumption of energy and non-renewable material is rapidly reaching, what many experts believe, unsustainable levels, which poses significant environmental challenges. Given the finite resources of the earth, sustainable production has been widely recognized as the next industrial revolution. It is a concept that requires a holistic approach to close the product life cycle and incorporate different aspects of sustainability throughout a product life cycle (Nasr et al., 2011; Umeda et al., 2012). As a result, remanufacturing has become one of the key enablers for sustainable production due to its effectiveness in closing the loop on material flows, extending product life cycle and reducing production waste and emission.

Remanufacturing is the process of bringing products back to sound working status, through the process of disassembly, sorting, inspection, cleaning, reconditioning, reassembly and testing, as shown in Figure 1.1 (Lund and Mundial, 1984). Not all the firms engaged in remanufacturing call themselves remanufacturers. Tire remanufacturers call themselves as “retreaders”; cartridge remanufacturers prefer to use the term “rechargers”, automobile remanufacturers consider themselves as “rebuilders”. Though different in name, they all share a common nature of bringing the used product to its as new condition; sometime even surpassing its initial standard.

The benefits of the remanufacturing can be summarized as a triple-win situation. The first win goes to environment, where the used components are diverted from waste stream to the reusable life cycle and thus lowering the resource and energy consumption, comparing with manufacturing a second new product (Kerr and Ryan, 2001). The second win goes to business, as material and energy saving not only can help companies meet the increasingly stringent environmental legislations, but also preserve the added value from the initial production stage, saving the cost up to 30-60% comparing with producing a new product (Sprow, 1992). The last win goes to customers, because the price of remanufactured products are usually much lower comparing to that of a newly manufactured product (Steinhilper, 1998). The growing awareness of the benefits of remanufacturing has made it an actively perused activity nowadays.

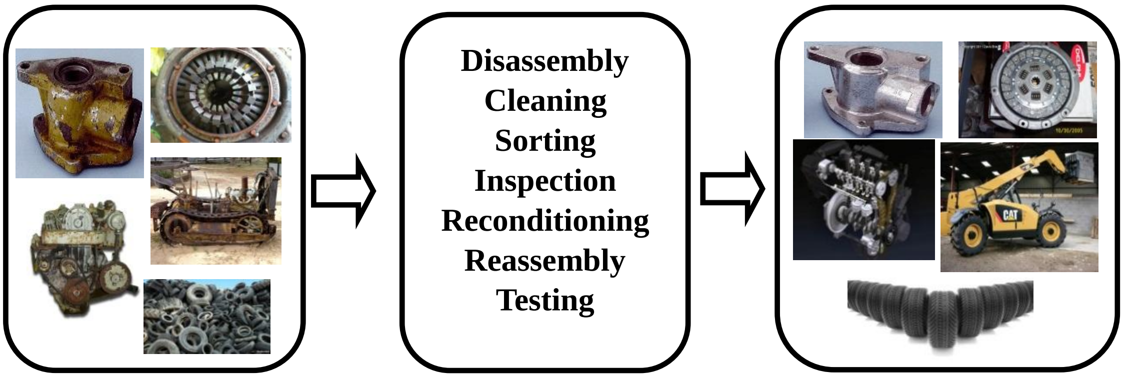


Figure 1.1: Remanufacturing processes

1.2 Motivation

The idea of remanufacturing as an academic research topic began to emerge only in early 1980s, with Robert Lund and Mundial's original remanufacturing study (1984). Since then, there has been increasing academic interest in remanufacturing arising from its recognized benefits and potential role in changing our society. The decision making on product remanufacturing is a rather complex issue. Business, engineering, market, economic and environmental factors can all affect the success of a remanufacturing endeavor. These important factors have to be investigated before carrying out product remanufacturing or during the product return stage, in order to maintain a profitable remanufacturing business. Moreover, the uncertainties involved in various dimensions, such as quality, quantities and timing of product return, market demand, inventory control, have further complicated the remanufacturing strategy planning issues and make it a challenge to determine the EOL options effectively for a product and its components (Goodall et al., 2014). In this regard, the proposed research will explore a logical way of determining whether certain products or components are feasible for remanufacturing at the initial product design stage as well as exploring the manner in which the product should be remanufactured during the disposal stage, through weighting and analyzing a comprehensive list of decision making factors.

Besides, previous research studies have indicated that barriers to the remanufacturing process can be traced to the initial product design stage (Ijomah et al., 2007). Product features and characteristics may have positive or negative impacts on the efficiency of remanufacture, depending upon decisions made during the design process (Charter and Gray, 2008). These have ignited the concept of

Design for Remanufacturing (DfRem) as a much pursued design activity (Sundin, 2004). The imperative for connecting design and remanufacture is further reinforced by Nasr and Thurston (2006), who stated that the full societal benefits of remanufacturing cannot be achieved unless DfRem is integrated with the product development process. Since design represents one of the earliest product development phases, it is important that the potential for remanufacturing is projected correctly in order that a product can be remanufactured viably and economically. Therefore, the proposed research will take a proactive measure to improve the potential of the product for remanufacturing, through developing an effective and efficient product design tool to address the remanufacturing issues at the product design stage.

1.3 Research Objectives and Scopes

The main objective of this research is to develop a Design for Remanufacturing and Remanufacturability Assessment (DRRA) tool, to be used at the early design stage to provide a systematic and holistic approach towards product EOL decision making, through addressing comprehensive aspects of remanufacturing issues. Meanwhile the tool also aims to improve the potential of product for remanufacturing by incorporating remanufacturing considerations into major aspects of product design. Besides, the tool can also be used during the product return/service stage to evaluate product remanufacturability based on their return condition and deliver a recovery plan which maximizes the economic profit meanwhile minimized the environmental impact. Though the methodologies will be discussed individually, they are

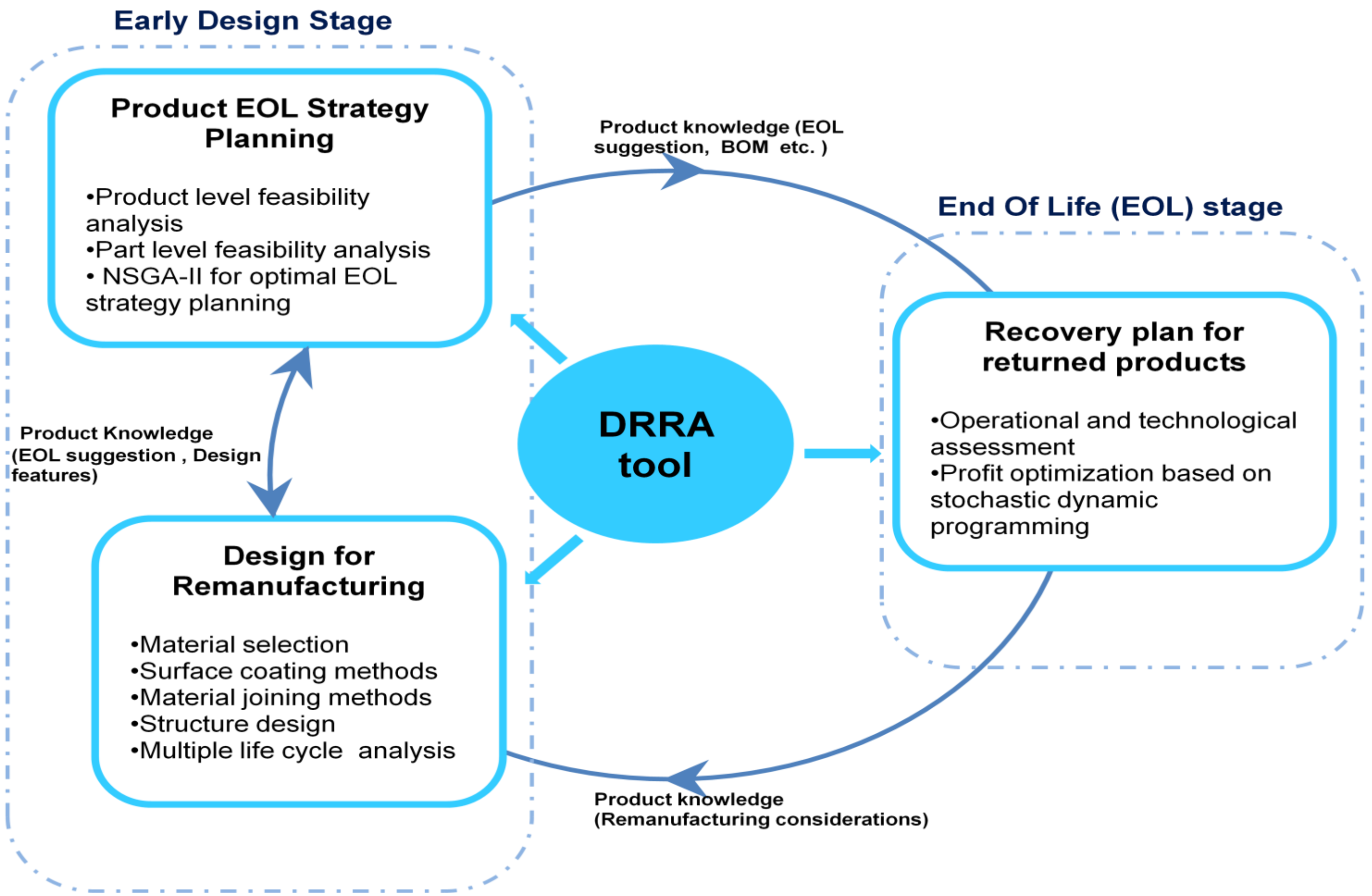


Figure 1.2: Flowchart for the proposed research work

connected internally by feeding forward and backward of the product knowledge, as seen in Figure 1.2. The flows of the product knowledge, along with the proposed decision support tools will form collectively the proposed DRRA tool.

Since the area of product design for remanufacturing and remanufacturability assessment is fairly wide, there is a need to zoom into a narrow scope. Therefore, some parts that might be interesting to conduct research on have to be excluded. The delimitation for this research is:

a) A complete sustainability problem is built upon three pillars, which are economic, environmental and societal pillars. However, due to fact that the social impact evaluation is generally considered to be still in its infancy and can hardly be quantified with a suitable indicator (Klöpffer and Renner, 2008, Jørgensen, 2013; Mattioda et al., 2015), thus only economic and environmental assessment will be used for the optimization of the remanufacturing decision making.

b) Within this research, case study has been put on automotive products, like engines and alternators, which have high embedded value, long technology life-cycle or high durability and thus are usually the desired candidates for remanufacturing. Meanwhile, it also covers electrical and electronic goods, such as hedge trimmer, telephones, for which there is less clear cut and a call for an analytical tool for gauging their suitability for remanufacturing. Besides, there are other product categories which might worth investigating, yet are delimitated from this research due to time constrains, such as office equipment, medical equipment and aerospace industry.

c) Remanufacturing know-how, which basically comprises the technology and the information required to remanufacture a product, plays a major impact on EOL decision making. The detailed examination and planning of the remanufacturing process and applied technology are not within the scope of this work. The proposed research work will instead, account this factor from a general abstract level.

1.4 Thesis Overview

After this introductory chapter, the next chapter (Chapter 2) summarizes the research works that are relevant to product design for remanufacturing and remanufacturability analysis. The insight gained and limitation identified from these literature, will constitute to the foundation as well as the motivation of this research work. In Chapter 3, the question of whether product and its components are feasible for remanufacturing will be addressed, through the proposed decision making tool. Meanwhile, the measure of improving the potential of the product/component for remanufacturing will be presented. Besides early product development stage, the DRRA tool is also developed to be used at the product return/service stage, to evaluate product remanufacturability based on their return condition and deliver an optimum recovery plan, which will be discussed in Chapter 4. Furthermore, Chapter 5 will discuss the integration of the DRRA tool and summarize the contribution of the proposed research work, followed by a critical review of this research and some suggestions for further research.

2. LITERATURE REVIEW

For the research work to be well grounded, and genuinely forward-moving, it is important to obtain a clear understanding of what has been done in this field. Therefore in this chapter, the research works that are relevant to product design for remanufacturing and remanufacturability analysis are described in section 2.1 and 2.2 respectively. Section 2.3 summarizes the related techniques and approaches that will be utilized in the research work. The insight gained and limitation identified from these literature, will constitute to the foundation as well as the motivation of this research work.

2.1 Design for Remanufacturing

2.1.1 DfRem Activities

Previous research studies have indicated that barriers to the remanufacturing process can be traced to the initial product design stage, and this has ignited the concept of 'design for remanufacturing' as a much pursued design activity (Ijomah et al., 2007).The definition of DfRem, as presented by Charter and Gray (2008), is *"a combination of design processes whereby an item is designed to facilitate remanufacture"*. DfRem is not only a part of "Design for X" (DfX) methodology, where X represents one of the aims of the methodologies, it incorporates a series of DfX strategies, such as design for core collection, design for upgrade, design for disassembly (Charter and Gray, 2008). Sundin (2004) suggested that DfRem stands for a collection of many tasks or considerations which prioritization may vary depending on the process needed of the products. Table 2.1 summarizes the design activities involved in the DfRem methodology:

Table 2.1: DfRem activities

• Design for core collection	• Design for restoring
• Design for disassembly/reassembly	• Design for multiple lifecycles
• Design for inspection	• Design for standardization
• Design for cleaning	• Design for handling
• Design for access	• Design for upgrade
• Design for durability	• Eco-design

2.1.2 Desired Product Characteristics for DfRem

Remanufacturing is often practiced by the Original Equipment Manufacturers (OEMs), who remanufacture their own products, contracted remanufacturers, who remanufacture the products under contract from the OEMs or customers, or independent remanufacturers (IR), who buy used products to remanufacture and resell them. However, the ability to resolve the difficulties in remanufacturing is most often owned by the OEM, since they control the product design stage and can potentially control remanufacture. Before an OEM considers designing their products for remanufacturing, they should examine whether their products possess the following qualities:

- Product is made up of standard interchangeable parts (Lund and Mundial, 1984).
- The cost of obtaining and reprocessing the core is low compared to the remaining value-added (Lund, 1998).
- Technology exists to restore product (Nasr and Thurston, 2006).
- Product technology is stable over more than one life cycle (Lund, 1998).
- Sufficient customer demand for the remanufactured product (Ayres et al., 1997)
- The core is durable and has high value (Charter and Gray, 2008).
- Potential to be upgraded (Shu and Flowers, 1999).

- There are channels for reverse flow of used product (Ayres et al., 1997).

2.1.3 Guidelines for DfRem

The most commonly used and effective approach to facilitate product design for remanufacturing is through providing design guidelines to steer a design towards higher remanufacturability. It is noted that the design guidelines proposed from various literature and research articles have presented a complementary but sometimes overlapping insight. An overview of the design guidelines for successful product remanufacturing is therefore conducted. The collated design guidelines will be presented in a generic and general manner and categorized according to the six steps that constitute the remanufacturing process, namely, core collection, disassembly, inspection and sorting, cleaning, refurbishment, and reassembly and testing. The results can be used to identify the opportunities for enhancing remanufacturing design, set goals and measure progress. Table 2.2 summarizes the literature sources drawn for composing these guidelines.

- Design for reverse logistic

End-of-life products usually need to be returned to the specific remanufacturing factory in order for remanufacturing to take place. If this process is not well dealt with, a large cost barrier could occur. For example, to facilitate core collection, the structure should be designed in such a way so as to minimize the occurrence of damage during transit. For products which movement requires the use of fork lifts, sufficient clearance and support at the base should be provided. In addition, structures that protrude outside a regular geometric volume should be avoided, since they are prone to become damaged during the transportation and may also hinder stacking during storage (Shu and Flowers, 1999). Meanwhile, labels, graphical communication and the form of the product should be placed on the exterior or interior surface of the product to communicate the information of the product. For example, Radio Frequency Identification (RFID) is frequently regarded as a form of label to allow a vast array of information to be held (Charter and Gray, 2008).

Table 2.2: References used in compiling list of guidelines for DfRem

Reference	Core return	Disassembly	Sorting & inspection	Cleaning	Refurbishing	Reassembly & testing
Amezquita et al. (1995)		✓	✓	✓	✓	✓
Mabee et al. (1999)		✓	✓	✓	✓	✓
McGlothlin and Kroll (1995)	✓					
Shu and Flowers (1999)	✓	✓	✓	✓	✓	
Sundin and Bras (2005)		✓	✓	✓		
Sundin and Lindahl (2008)		✓		✓	✓	✓
Charter and Gray (2008)	✓	✓	✓	✓	✓	✓
Ijomah et al. (2007); Ijomah (2009)		✓	✓	✓	✓	✓
Yüksel (2010)		✓	✓	✓	✓	

- Design for Disassembly

Disassembly is not a simple reversal of assembly. Many permanent techniques which have been developed to realize and fasten the assembly process, such as plugging, pressing, forming, sonic welding, and adhesive, can cause problems for the disassembly process (Mabee et al., 1999). Basically, there are four areas that need special attention in design for disassembly: 1) joint selection: the selection of the types of joints would critically affect the efficiency of the disassembly process. Non-permanent joints are generally preferred since they are simple to loosen (Mabee et al., 1999), e.g., bolt joints are usually preferred over adhesives; 2) plan for non-destructive disassembly: disassembly is desired to be non-destructive (Bras and McIntosh, 1999). After the disassembly, the components are expected to be separated without being damaged or cause damage to other parts of the product. In addition, it is desirable for the fasteners to be reused; 3) Prevent corrosion/rust: corrosion and rust are the greatest hindrance reported in an automotive industry survey (Charter and Gray, 2008). Prevention of corrosion and rust will lead to better isolation of parts from the elements, using the less or non-corrosive materials or switch to other fastening mechanisms; 4) Clear instructions for disassembly steps: the disassembly instructions should be properly displayed on the returned core to facilitate the disassembly process. This is particularly important for third-party remanufacturers, who do not have detailed specifications of the products.

- Design for Sorting and Inspection

Depending on the various inspection results, parts are sorted into three classes, namely, reusable without reconditioning, reusable after reconditioning, and not reusable. To facilitate the sorting and inspection process, Parts fulfilling the same function should have identical or distinctly dissimilar features. For example, to differentiate the gears that fulfil different functions, gears could be made of different color coding systems or have a specific number on them to identify them easily (Mabee et al., 1999). Meanwhile, determining and accessing the point for testing should be made easy and the time required for the inspection of the parts should be minimized. Design features, such as the sacrificial parts for indicating the component’s condition over time should be encouraged. Sensors can also be embedded to record the useful data and communicate the information over time (Ilgin and Gupta, 2011).

- Design for Cleaning

Cleaning is the most energy and labor intensive process in remanufacturing (Shu and Flower, 1999). Therefore, it is important to take the cleaning process into considerations during design, otherwise a simple cleaning operation can become too laborious, expensive, or even impossible. Firstly, texture and geometrics that facilitate easy cleaning are encouraged, such as a relatively flat surface which has a lower tendency to trap dirt or collect residue from cleaning (Amezquita et al., 1995). Secondly, structures that require fewer variation of cleaning methods are always preferred. In this way, the cleaning process can be simplified. The material of the product that requires special cleaning methods should be avoided as much as possible, so as to minimize the cleaning cost as well as waste generation (Shu and Flowers, 1999). Thirdly, during the cleaning process, labels and instructions which carry the product information on the component should be prevented from being washed away, since this may cause problems in subsequent refurbishment and reassembly processes (Sundin and Bras, 2005).

- Design for Reconditioning

During the refurbishment process, parts will be restored geometrically and properties to be restored with surface treatment. To facilitate this process, bulky and slightly over-designed components are preferred than products with thin and less material, as the former could provide more margin of materials to be worked on with during refurbishment of components (Shu and Flowers, 1999). Surfaces should also be designed in such a way that they have strong wear resistance, since the product may need to go through several use cycles. Moreover, it is appropriate to increase the dimensions to maximize usage cycles since part wear tolerance and material removal must be considered in these areas (Mabee et al., 1999). In addition, a proper incorporation of platform and modularity design can also increase the product reusability, through allowing the defunct aspects to be grouped and removed easily while retaining the useful aspects of the product (Charter and Gray, 2008).

- Design for Reassembly and Testing

Designing products for reassembly and final testing can be improved from the following two aspects. Firstly, during reassembly, the number of the adjustments should be kept low and adjustments should be easy to make and independent from each other. Also the design should be flexible enough to be able to adapt to future technology migration as well as accommodate new configurations of the part.

The lists of design guidelines have provided an understanding of the barriers that may be encountered during remanufacturing processes, as well as directions to enhance the efficiency of product remanufacturing. Appendix I provides more detailed remanufacturing requirements and their related design criteria. Remanufacturing requirements are gathered from the feedback of remanufacturers with respect to improving the efficiency of the remanufacturing process. The design criteria are interpreted and "translated" from the remanufacturing requirements, bringing abstract requirements to concrete design specifications. It aims to provide the product designers with the most comprehensive guidelines to enhance product design for remanufacturing. However, the designers may still need to make proper judgment during the design of each individual product.

Though straightforward and comprehensive, the approach of design guidelines for DfRem has been criticized as overly daunting, since it is impossible for designers to consider all these criteria simultaneously and some of the remanufacturing design requirements are intrusive on traditional design (Zwolinski et al., 2006). In addition, there are other issues that the design guidelines do not fully address, such as the subjectivity and customization guidelines (Hatcher et al., 2011).

2.1.4 Design for Remanufacturing Tools

The subsequent development on DfRem focuses on formulating the design tools and methods to address and alleviate the problems associated with the remanufacturing process during the product design stage.

One of the trends is to develop mathematical models, software tools or statistics reference for improving product design for remanufacturing, assessing product remanufacturability and prioritization of remanufacturing design criteria, as summarized in Appendix II. Sundin (2004) has developed the "RemPro Matrix", which identifies the relationship between different product properties and specific remanufacturing steps, such as ease of access is closely related with disassembly, cleaning and inspection process. Ijomah et al. (2007) have proposed some fundamental steps required to improve the robustness of DfRem methodology. However, most of these models and tools still remain within the academic realm and have hardly been utilized in the industry today. Some of the reasons as indicated by Hatcher et al. (2011), are that these design tools are quite complex and lack of applicability to the entire lifecycle of a product. Furthermore, most of these tools are only applicable at the late design stage when most of the decisions have already been made. The reluctance of the company to share their in-house methods, tools and knowledge with the outside world also leads to the barrier between the academic and the industry world.

Another trend of DfRem is to use existing design tools, such as modularization and QFD, that are considered relevant for improving the remanufacturability of products. The table in Appendix III summarizes the design aids that have been used to facilitate DfRem. As most of the designers are familiar with these design tools, this would make the integration of DfRem a much simpler job. However, the problems associated with these tools are that most of them are not developed for DfRem purposes and fail to address all the design aspects that affect the potential of a product for remanufacturing. Therefore a holistic guidance and assistance on how to carry out DfRem with these tools would need to be further explored.

2.1.5 Challenge and Future Trends of DfRem

Despite the appealing benefit of carrying out DfRem, there are still barriers and complications that companies may face. First of all, comparing with other DfX issues, such as design for assembly (DFA), DfRem is usually not given the priority, since most OEMs' main focus is on the manufacturing and usage phases. Whenever there is a conflict between DfRem and other prioritized issues, such as DFA and manufacturing, DfRem usually loses its importance and is viewed as less useful in terms of time and cost due to the lack of awareness among designers. Therefore a holistic life cycle analysis is necessary to quantify the impact of remanufacturing improvement design feature. Secondly, some OEMs play down on remanufacturing deliberately through product design to stifle the independent remanufacturing activities. This is because none of the OEMs have strong desire to enhance remanufacturability for benefitting the independent remanufacturers, who are viewed as strong competitors of their own products. Thirdly, DfRem guidelines, as presented in section 2.1.3, involve a variety of design issues, which will form a new set of challenges that producers may not be prepared to deal with, not to mention there are still confusions around the definition of remanufacturing (Hatcher et al., 2011).

The future study on DfRem can continue to work on developing methods and tools, especially the ones which incorporates life cycle thinking and also can be used effectively at early design stage, as DfRem is most effective in this stage when few design decisions have been made and less technical data is defined (Amezquita et al., 1995; Zwolinski et al., 2006). More case studies, comprising the entire spectrum of the remanufacturable products, are needed for further validation of researchers' findings or design tools. In addition, though the design criteria for remanufacturing have been reviewed comprehensively, the method for integrating them fully into the design process still needs further exploration.

2.2 Product Remanufacturability Assessment

Among the research works that are related to EOL assessment, two main streams, namely product demanufacturabilty assessment and product remanufacturability analysis, can be identified. Even though both streams deal with the optimization of product EOL disposition, the fundamental differences remain on the final destination of EOL products. Demanufacturing focuses on part level components reuse, recycle, remanufacture, landfill or disposal, through dismantling of EOL products (Johnson, 2002; González and Adenso-Díaz, 2005; Jun et al., 2007; Staikos and Rahimifard, 2007; Chan, 2008; Gehin et al., 2008; Zhang et al., 2013). On the other hand, product remanufacturing, which is also the focus of this research, deals with recovering the entire EOL products to as new condition. The research work on evaluating remanufacturing strategy can usually be observed in two major aspects, product level remanufacturability assessment and parts level remanufacturability assessment.

2.2.1 Product Level Remanufacturability Assessment

Many studies have been based on the economic benefits to assess the feasibility of product remanufacturing, since remanufacturing without a sound monetary foundation will almost certainly fail (Subramoniam et al., 2009). The decision support tools are necessary to help the decision makers decide whether they should invest in remanufacturing any of their products. King and Barker (2007) have applied the Delphi technique to build a robust research agenda and identified selling "use" instead of "product" as a novel remanufacturing business model. A remanufacturing facility cost model is developed by Sutherland et al. (2010), which includes product, operation, inventory and transportation-related costs. The output of this work can be used for facility planning for remanufacturing operations. Chen and Chang (2012) have built an economic model to analyze the pricing and production lot-sizing in a closed-loop supply chain and used this model to investigate the possibility to combine remanufacturing with manufacturing operations. A cost model has been developed by Xu and Feng (2014) to evaluate the benefit of remanufacturing techniques quantitatively and assist decision making on end-of-life strategies. However, since the products could be returned multiple times, it is possible that the material, labor and overhead cost could only be recaptured and a profit made after several sales, which makes the determination of the profit of remanufacturing even more complicated. The transfer of pricing to allocate a portion of the initial production cost to the remanufacturing division has been discussed by Toktay and Wei (2011), aiming to achieve the optimal financial results of the firm. However, mere focus on economic feasibility of product remanufacturing could lead to inadequate support for remanufacturing decisions and result in sub-optimization of the entire supply chain, since there are other factors, such as ecological factors and business factors that are also influential on remanufacturing decisions. Therefore, some studies have focused on developing decision-making framework, which comprises of a comprehensive set of strategic factors, such as customer demands, environmental consideration. For example, a software tool has been developed by Kobayashi (2005), to assign the appropriate life cycle options to the product and its components, taking into account the business, production and environment perspectives. Remery et al. (2012) have utilized Fuzzy-TOPSIS method to assist the multi-criteria EOL decision making. Subramoniam et al. (2010) have used survey ranking to prioritize 12 deciding factors for remanufacturing, and built a comprehensive Remanufacturing Decision-Making Framework (RDMF). Other principal operation control issues that hinder remanufacturing have been identified by Ijomah (2009), which include the uncertainty of demand volume variability, core quality, the difficulty of knowledge acquisition and process as well as the flexibility issue. In addition, some commercial tools have also been available for remanufacturing assessment and supply chain management (Levelseven, 2015: Activate, 2015; NCMS, 2015; Ipoint, 2015).

With the awareness that design determines two thirds of the product remanufacturing efficiency, some researchers have started to assess product remanufacturability specifically from the design perspective. Lund (1998) has proposed seven major criteria for product remanufacturability assessment at the design stage, based on the study of 75 routinely remanufactured product types. Amezquita et al. (1995) has consolidated design metrics to measure effectively and efficiently the remanufacturability of product design, which includes design characteristics that facilitate remanufacturing, the principal driving factors for remanufacturing as well as the existing remanufacturing guidelines and practices. Adapted from DFA metrics, Bras and Hammond (1996) have developed the metrics for assessing the remanufacturability of a designed product in a qualitative way. Besides, an integrative approach to assess the technical, economic and environmental feasibility of the returned products and facilitate the decision making on whether the product should be remanufactured, has been proposed by Du et al. (2012) and validated by a machine tool remanufacturing study.

2.2.2 Parts Level Remanufacturability Assessment

While the literature and theories focusing on strategic decision making for product remanufacturing are gaining popularity, the available framework on deciding the EOL strategies at the component level during the product service stage is relatively limited. Even for the routinely remanufactured products, not all their components are suitable for remanufacturing. Some components are disposed of due to severe wear and corrosion while others are recycled to recover the raw material (Smith and Keoleian, 2004). Thus far, decision making on components EOL strategy planning relies mostly on ad hoc engineering judgement, which may be subjective and imprecise. Therefore, there is a need for systematic and comprehensive decision support tools to evaluate remanufacturability at the component level so as to help the decision makers make better EOL choices.

Disassembly, which allows the separation of the reusable and non-reusable components for further processing, is closely related with EOL strategy determination and regarded as a new frontier to product EOL management. Many researchers have proposed different methodologies to measure the disassemblability of a product and generate an optimum disassembly sequence. For example, Gungor and Gupta (1997) have proposed a disassembly sequence generation heuristic which could generate the optimum disassembly sequence for a product. Pbioore et al. (1998) have used Petri Nets to study disassembly planning. Differences among these methods are the techniques applied to solve the problems. Moreover, the factors that affect the EOL strategy include not only the disassembly sequence, the disassembly time, the disassembly cost, but also the benefits from reuse and recycling the components (Veerakamolmal and Gupta, 1999). There is, therefore, a growing amount of work on proposing methods for generating “recovery plans” and balancing the value of the reclaimed parts with the disassembly cost. Isaacs et al. (1997) have proposed a methodology which to measure the disassembly and recycling potential for automobile design. González and Adenso-Díaz (2005) have introduced a model which could determine the optimal EOL strategy for each component and the subsequent disassembly strategy that leads to the highest profits.

Besides, confronting with the increasingly restrictive environmental regulations, it is not only critical to maintain economic profitability, but also crucial to minimize the environmental impact through product life cycles, which has led to the multi-objective decision making problems (Hula et al., 2003). Traditionally, these two objectives were either combined linearly to form a scalar objective, for example, Ghazalli and Murata (2011) have converted environmental impact into environmental cost and integrated it with economic cost to determine the component EOL strategies; or else only one objective is optimized and the other one is turned into a constraint, such as the EOL decision model provided by Lee et al. (2010), which optimized economic profit and used environment regulation as a constraint to revise the EOL options.

2.2.3 Challenge and Future Trends of Remanufacturability Assessment

The decision making on a product and its components remanufacturing is a rather complex issue. Business, engineering, market, economic and environmental factors can all affect the success of a remanufacturing endeavor. These important factors have to be investigated before carrying out product remanufacturing and are crucial for maintaining a profitable remanufacturing business. Moreover, the uncertainties involved in various dimensions, such as time and quantities of product return, market demand, inventory control, have further complicated the remanufacturing strategy planning issues and make it a challenge to determine the EOL options effectively for a product and its components (Goodall et al., 2014). In this regard, there is an urgent need of a decision support tool which can provide a systematic and holistic approach towards EOL decision making, through addressing comprehensive aspects of remanufacturing issue as well as weight in the uncertainty involved in product remanufacturing process. Furthermore, research work can also focus on developing databases or knowledge-based systems, drawing experience from the existing remanufacturing knowledge and practices, to facilitate the new assessment tools.

2.3 Related Methodologies and Approaches

2.3.1 Design for Environment

DfE is to design a product such that the environmental impact throughout the life cycle is minimized (Ilgin and Gupta, 2010). Some researchers adopted Quality Function Deployment (QFD) methodology to consider environmental criteria and customer requirements simultaneously for product design (Cristofari et al., 1996; Zhang, 1999; Mehta and Wang, 2001). Some uses Life Cycle Analysis (LCA) to assess the environmental impact (Veerakamolmal and Gupta, 1999; Grote et al., 2007). There are studies that focus on developing tools to evaluate the product design with respect to environmental criteria, such as Green Design Advisor, which considers metrics related to product design information and combines these metrics using the multi-attributes value theory to obtain an overall score (Feldmann et al., 1999). Lye et al. (2002) proposed EcoDe, which is a computer-based design evaluation tool, to assess the environmental impact of the components of the product. Analytic Hierarchy Process (AHP) and the multi-criteria technique are used in this tool to calculate the environmental index.

Most of the time, DfRem is viewed to be under the umbrella of Design for Environment (DfE). Compared with DfE, DfRem is a relatively new and unexplored research area. The literature on DfE thus, provides a valuable insight on the approaches that are likely to be applicable in DfRem. For example, DfE literature emphasizes the importance of early integration of environmental requirements, the positive impact from management commitment, and the indispensability of tools to address the environmental requirements, which inspires the ways towards successful DfRem implementation (Quella and Schmidt, 2003). However, DfE and DfRem are not interchangeable and sometimes, they are even in conflict with each other. For example, DfRem may require components to be over-designed such that in subsequent remanufacturing operations, e.g., machining and grinding, can be performed easily; on the other hand, DfE may require components to be designed with minimum use of materials so as not to waste resources. The difference between them emphasizes the importance of exploring DfRem as a stand-along entity.

2.3.2 Life Cycle Analysis

To evaluate and assess the environmental impact attributed to the life-cycle of a product and identify improvement potential, a large number of assessment methodologies and corresponding indicators have been developed (Hertwich et al., 1997; Robèrt et al., 2002; Umeda et al., 2012; Kobayashi, 2006). Among these proposed tools, Life-Cycle Assessment (LCA) methodologies are the most widely used. Its underlying philosophy is to provide a comprehensive view of the environmental aspects of a product or process throughout the life-cycle and an accurate analysis of the environmental trade-offs in product and process selection (Corporation and Curran, 2006). Figure 2.1 depicts a framework for LCA by the Society of Environmental Toxicology and Chemistry (SETAC) (Rebitzer et al., 2004). Problems, such as shifting from one stage of the life cycle to another, from one type of problem to another, from one location to another, can be avoided through this integrative approach, since all the life cycle stages are included in the evaluation (Zhang, 1999; Mehta and Wang, 2001; Grote et al., 2007; Sakao, 2007).

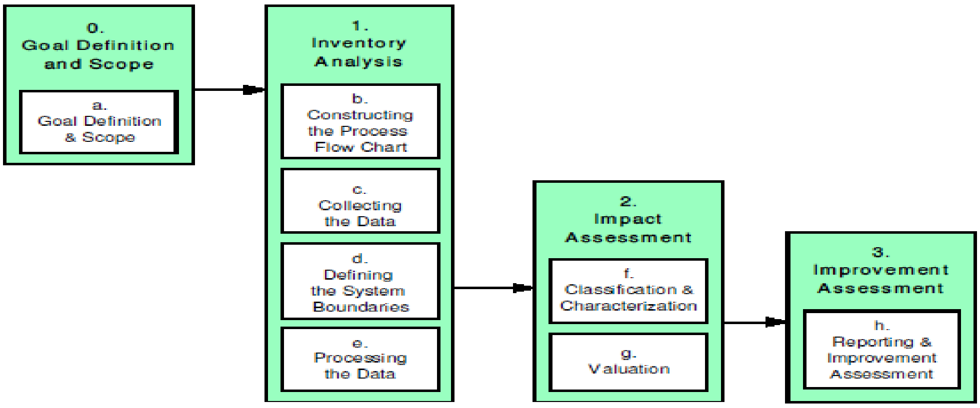


Figure 2.1: LCA Framework (Rebitzer et al., 2004)

However, one of the limitations of carrying out an LCA is that a significant amount of data is required. Even though some software programs with inventory data are available, gathering data for specific product processes still remains a challenge, as most of these data are not available to the public or not provided in a standard format (Huijbregts et al., 2006). Meanwhile, generally only little information on product or process is available during early product development stage, which has limited the applicability of LCA in the early design stage. Furthermore, as remanufacturing can close the loop of material flow effectively and has great potential to extend the number of product life cycle from one to multiple, the resulting complex life cycles have to be modeled and assessed by decision makers for a better understanding of the relative benefit of the alternative design strategies and thus making decisions on improving product design and EOL recovery system.

2.3.3 Multi-Objective Decision Making Analysis

Making an optimum decision for diverse applications from a finite set of feasible alternatives and predetermined number of criteria is often regarded as a multi-criteria decision making (MCDM) problem. MCDM methods, such as Technique Of ranking Preferences by Similarity to the Ideal Solution (TOPSIS) (Jee and Kang, 2000; Shanian and Savadogo, 2006; Rao, 2008; Zeydan and Çolpan, 2009; Govindan et al., 2013), elimination and choice expressing the reality (ELECTRE) (Milani and Shanian, 2006; Shanian and Savadogo, 2006; Shanian et al., 2008; Laforest et al., 2013), Analytic Hierarchy Process (AHP) (Cao et al., 2006; Dweiri and Al-Oqla, 2006; Rao, 2008; Jiang et al., 2011), preference ranking organization method for enrichment evaluation (PROMETHEE) (Chatterjee and Chakraborty, 2012; Çalışkan et al., 2013; Peng and Xiao, 2013), Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) (Opricovic and Tzeng, 2004; Opricovic, 2011; Shemshadi et al., 2011), and simple additive weighting method (Quigley et al., 2002; Dehghan-Manshadi et al., 2007; Fayazbakhsh et al., 2009), are the most notable. Though each technique has its own characteristics, they share a similar systematic evaluation procedure which involves the following three steps (Yurdakul and Ic, 2009):

1. Determine the relevant criteria and feasible alternatives
2. Attach the numerical measures to the relevant importance of the criteria considered and the impact of the alternatives of those criteria
3. Determine a ranking score of each alternative by processing the numerical values

Among these MCDM methods, TOPSIS is chosen in this research to evaluate and compare the feasibility of design candidates. The TOPSIS method is proposed by Hwang and Yoon (1981) based on the idea that the best alternative should have the shortest distance from an ideal solution and farthest from the non-ideal solution. It is a widely used MCDM tool due to its simplicity and effectiveness. The output of this method can be a preferential ranking of the alternatives with numerical values (Shanian and Savadogo, 2006). The application of TOPSIS in the product design stage has been observed from many published works. For example, Shanian and Savadogo (2006) have applied the TOPSIS analysis to select optimum materials for metallic bipolar plates for polymer electrolyte fuel cell. Boran et al. (2009) have selected the suppliers successfully, who are able to provide the buyer with the right quality products and/or services at the right price, at the right time and in the right quantities through the use of the TOPSIS methodology.

The traditional TOPSIS method defines the problem in the form of a decision matrix filled with crisp data, assuming that the performance value is defined precisely. However, in some real world decision making situations, due to time pressure and limited information or knowledge about the problem domain, decision makers may prefer to express their evaluation with ranges, verbal descriptions or linguistic variables, rather than exact numbers. Therefore, some researchers have proposed to combine TOPSIS with the Fuzzy Set Theory for expert evaluation and adopted this Fuzzy TOPSIS method in the area of decision making on green supply chain (Wang and Chan, 2013), supplier or outsourcing manufacturing partner selection (Chen and Hung, 2010; Govindan et al., 2013), plant location selection (Ertuğrul and Karakaşoğlu, 2008), risk assessment (Samvedi et al., 2013), material selection and design (Rathod and Kanzaria, 2011; Mirhedayatian et al., 2013), etc..

2.4 Summary of the chapter

This chapter has provided an overview of the existing Design for Remanufacturing approaches. The problems of the existing DfRem tools and guidelines, such as over daunting, lack of life cycle thinking, overly complex, have been identified, which address the need of a DfRem tool which can be used effectively at the early design stage and can be integrated easily with the original design process. On the other hand, research works that are related to the product and part level remanufacturability assessment have also been reviewed in this chapter. Though diverse and informative, there are still some limitations of the existing approaches, such as a lack of a holistic and systematical tool, which can weigh in comprehensive remanufacturing considerations and meanwhile achieving both economic and environmental optimizations. Besides, EOL decision making at the early development stage and product return stage, presents different problems sets, such as the availability of product information, which most of the research work did not mentioned much and distinguish between them. Hence there is a need of tools to be developed specifically to facilitate the decision making at both of these stages. Overall, the insight gained and limitation identified from these literature, will constitute to the foundation as well as the motivation of this research work.

3. EARLY DESIGN STAGE

Products designed with a remanufacturing reclamation strategy would perform very differently during the remanufacturing process, as compared to those which do not incorporate any remanufacturing consideration during the initial design stage. The decision to include remanufacturing as a part of product design should be made as early as possible, as the freedom of design decreases along the product development process. Therefore, the question of whether the product and its components are feasible for remanufacturing and the method to improve their remanufacturability through proper product design would need to be addressed carefully during the early product development stage. In this regard, this chapter presents a holistic approach to evaluate the viability of conducting remanufacturing for a product and its components. Meanwhile, a product design support tool has also been proposed, aiming to address the various remanufacturing concerns and make robust and effective design decision at the product design stage.

3.1 EOL Strategy Planning

3.1.1 Introduction

The decision to include remanufacturing as a part of product design should be made as early as possible, however this decision making is a rather complex issue as it involves high level of uncertainties of time and quantities of product return, market demand and inventory control, etc. Even though some relevant work has been identified, there are still limitations from the following viewpoints. First, as the research work on decision support for remanufacturing strategy planning is still in its infancy, there is a lack of a holistic approach that can address the various aspects of remanufacturing considerations and ensure the completeness of financial and environmental decisions. Second, given the multi-criteria nature of EOL strategy planning, the solution is usually a range of possible choices rather than an exact one. The decision method has yet to be described that can determine a set of optimum remanufacturing strategies efficiently and quantitatively and provide more flexibility for remanufacturing strategy planning. Third, due to the uncertainty that involved in the EOL strategy planning process, the decision model which can analyze the impact of situational variables effectively on EOL decision making has not been found in any literature.

In this regard, a decision support tool dealing with remanufacturing strategy planning is proposed in this chapter. It aims to provide a systematic and holistic approach towards EOL decision making, through addressing comprehensive aspects of remanufacturing issues. A Genetic Algorithm, namely NSGA-II has been adopted to determine a Pareto set of optimal EOL solutions, which will facilitate the effort of decision makers to maximize the environmental benefit of remanufacturing for a given economic profit. In addition, the rapid calculation of Pareto solutions through the proposed methodology also permits extensive sensitivity analysis so as to understand thoroughly the impact of situational variables on EOL decision making, i.e. Pareto frontier, and thus leading to improved strategy planning and better product design. Hence, the output of the proposed methodology is essential for making the following decisions:

- Evaluating the feasibility of a product and its subassemblies/components for remanufacturing and redesigning the process or product if necessary;

- Determining a Pareto set of optimum solutions corresponding to maximum environmental performance for a given economic cost as well as suggesting EOL strategies for subassemblies/components;
- The depth or extent of disassembly when remanufacturing is uneconomical;
- Investigating a large number of scenarios as necessary in EOL decision-making (Pareto frontier), such as change of remanufacturing cost, product design, landfill cost, and suggesting appropriate EOL strategies to accommodate the change of situational variables.

3.1.2 Framework for Product EOL Strategy Planning

To assist EOL decision making, especially for companies which are carrying out remanufacturing or planning to engage in remanufacturing business, a four-step decision support tool is proposed and shown in Figure 3.1. The first step consists of a sequential examination of product level remanufacturing characteristics, aiming to distinguish quickly a product that is feasible for remanufacturing from a product that is not a viable candidate for remanufacturing. Next, detailed subassembly/component level characteristic examination will be carried out to identify the viable subassemblies/components for remanufacturing. In the third step, a multi-criteria decision making analysis is conducted to generate a Pareto set of EOL solutions, from which decision makers can choose to accommodate various remanufacturing requirements. The last step will incorporate sensitivity analysis to examine the impact of situational variables or product redesign on EOL strategy planning, thus leading to improved strategy planning and better product design. The details of the proposed methodology are explained as following:

Step I: product level feasibility analysis

The product level feasibility analysis is developed to distinguish a product that should be designed for remanufacturing quickly from a product that should be targeted for demanufacturing strategy, through a sequential examination of characteristics that are related to product remanufacturing performance, as elaborated next.

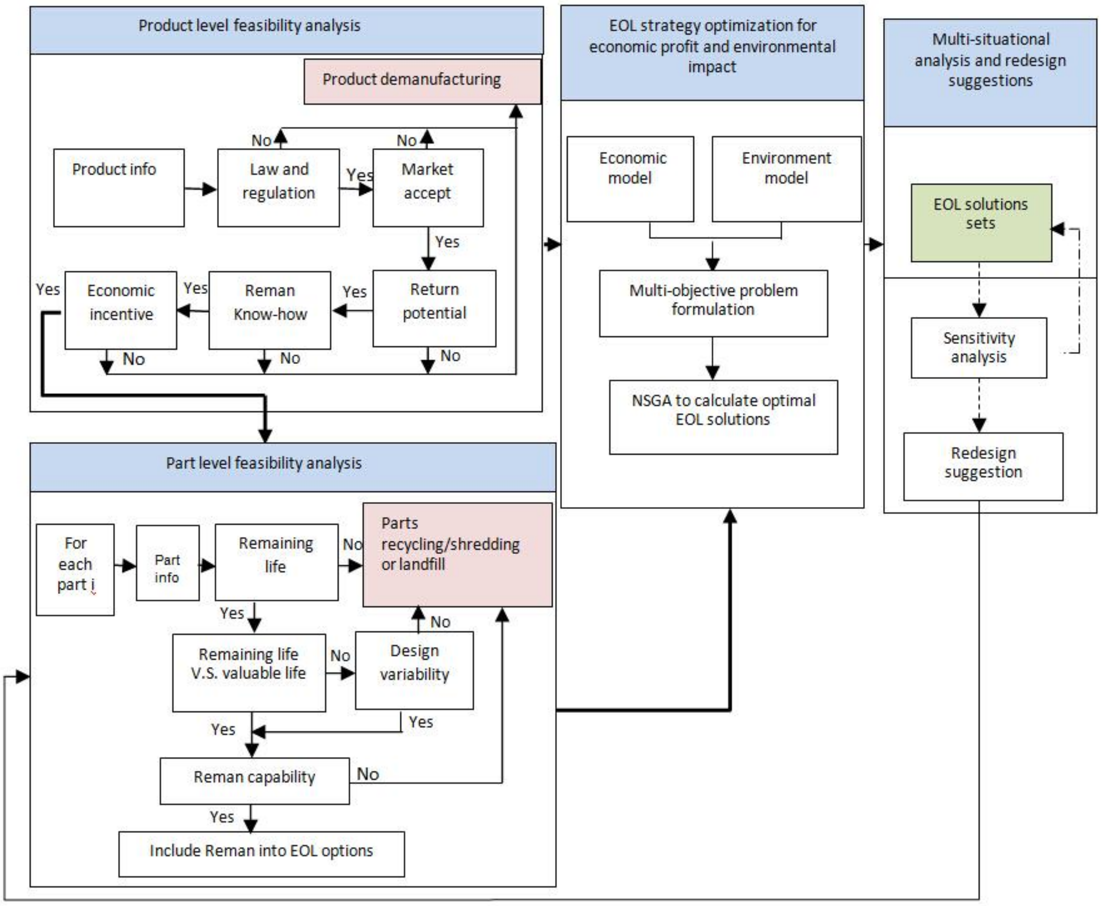


Figure 3.1: Flowchart of the EOL decision support tool

- **Compliance with laws and regulations**: The impact from environmental legislations varies for product remanufacturing. On the positive side, these regulations address the necessity of sustainable development and thus promote remanufacturing development. However, some of them may hamper remanufacturing to various degrees. For example, the Restriction of Hazardous Substances (RoHS) Directive may hinder the markets for remanufactured product which contain substances now termed 'hazardous' (Charter and Gray, 2008). As mentioned by Gerrard and Kandlikar (2007), the concentration from End of Life Vehicles Directive on recycling and energy recovery may discourage higher forms of waste management hierarchy such as remanufacturing. Therefore, the impact from legislations on remanufacturing needs to be understood in order to design successful product for remanufacturing.

- **Market demand/acceptance**: This criterion is to evaluate to the extent to which the design concept is expected to occupy a competitive position in the market after being remanufactured. For product types which have a long technological cycle, like the diesel engine, heavy duty vehicles, etc., remanufacturing is usually feasible since most of those products can still remain competitive in the aftermarket. For product types which have rapid technology obsolescence, remanufacturing might not be a feasible EOL option, unless the design features that are likely to suffer early obsolescence can be decoupled easily from the more stable product platforms, or secondary and tertiary markets, which usually do not require the product to possess the latest technology, can be found.

- **Return potential**: It is important to predict the likelihood that a product will be returned successfully to the remanufacturing site at the end of its useful life. Some remanufacturing companies purchase retired products from collection points in the existing distribution and disposal networks, or directly from customers; some OEMs establish leasing arrangements to retain the product ownership and have product returned at a specified time; others incorporate "core charge" to their products and reimburse the customer only when the product is returned properly, etc. Failing to identify the product return channels may cause the infeasibility of carrying out product remanufacturing.

- **Remanufacturing know-how**: Remanufacturing know-how comprises the technology and the information required to remanufacture a product. Decision makers need to examine whether the technology and technical skills needed to restore the product will be available when the product reaches its EOL stage, such as the technology to repair wear in low stress areas of cast iron engine blocks, the skill to disassemble a sophisticated joint. Meanwhile, the availability of the technical data package to restore a product needs to be examined, which includes material specifications, dimensional tolerance, historical information that stores the product refurbishment history, etc.

- **Economic incentives**: Economic incentives come from both product value and product recoverable value. Decision makers need to determine whether the product has undergone sufficient value-added operations (like manual or automated operations) to make remanufacturing worthwhile. On the other hand, they also need to estimate whether a product can be economically recoverable at its EOL stage.

Hence, if the design concept performs satisfactorily for all the criteria, it is considered as a feasible candidate for remanufacturing and will enter into the second stage for part level evaluation. Failing to meet one or more of the criteria will indicate that remanufacturing is not practical. In this case, demanufacturing will be the fallback position and the remanufacturing strategy planning process will stop.

Step II: part level feasibility analysis

Even though a product is suitable for remanufacturing, not all its components can be remanufactured. Therefore, the purpose of this stage is to determine the feasible EOL options for each subassembly/component and rule out the ones that are not viable for remanufacturing.

- **Remaining useful lifetime**: Useful lifetime is defined as the time from product/part purchase until the product/part no longer meets its initial requirement, due to ‘failure’ or ‘physical degradation’ (Rose, 2000). The remaining useful lifetime of a component after being remanufactured should correspond to more than at least one usage period, such that the quality of remanufactured product can be ensured.

- **Remaining useful lifetime versus valuable lifetime**: Valuable lifetime refers to the time that a product/part is expected to occupy a competitive position in the marketplace, until it becomes obsolete or less desirable due to external factors, such as market pressure, scientific advances and company focus. If the valuable lifetime is longer than its useful lifetime, the part will usually have high remanufacturing potential. However, if the valuable lifetime is shorter than the useful lifetime, the part will be evaluated for the next criterion for design viability examination.

- **Design viability**: This evaluation criterion is meant to encourage designers to rethink the design concept in order to prolong the valuable lifetime of a part and avoid overdesign of the parts, such as incorporating modularity design to facilitate upgrade, replace or other forms of enhancement. If the review suggests negative on design viability, recycling or landfill of the part will be suggested.

- **Remanufacturing capability**: Remanufacturing capability will be assessed from the availability of facility, equipment and trained personnel to perform the remanufacturing procedures. When internal resource is insufficient to meet remanufacturing requirements, feasibility to outsource the parts for remanufacturing might also be explored.

Therefore, if subassemblies/components can pass the feasibility assessment successfully, remanufacturing will be included as one of their feasible EOL solutions, otherwise only shredding/recycling and landfill will be considered. Once all the feasible EOL strategies have been identified for each subassembly and component, the evaluation process will advance to step III.

Step III: EOL strategy optimization for economic profit and environmental impact

To optimize the EOL strategy planning, the value of economic profit and environmental benefit needs to be estimated firstly by using Equations 3.1-3.5. It is noted that energy has been chosen as the indicator for environmental performance, as it has strong correlations with the various environmental metrics, such as global warming potential, air pollutants emissions (Hula et al., 2003). The overall economic and environmental metrics calculated using Equations 3.6 and 3.7 represent the objective functions for the optimization problems. Both objectives are functions of X_{ij}, which represents the EOL strategy j assigned for component i.

The fundamental constraints in this optimization problem include (a) there is only one EOL option for each subassembly or component, namely (1) remanufactured, (2) shredded/recycled, (3) landfilled, (4) disassembled or (5) remained within the parent assembly; (b) if assembly k is remanufactured, shredded/recycled or landfilled as a complete entity, all of its subcomponents i should remain within this assembly; (c) if assembly k is to be disassembled, all of its subcomponents i will be separated for remanufacturing, shredding/recycling or landfill. These constraints are expressed in Equations 3.8-3.10.

$$Eco\_Cost_{Reman_i} = C_{Reman_i} + C_{Miscellaneous_i} \tag{3.1}$$

$$Eco\_Cost_{\mathrm{Shred/Rc_i}} = C_{Shredding/Recycling_i} + C_{Newpart_i} + C_{Miscellaneous_i} \tag{3.2}$$

$$Eco\_Cost_{Lf_i} = C_{Landfill_i} + C_{newpart_i} + C_{Miscellaneous_i} \tag{3.3}$$

$$Energy\_Recovered_{Reman_i} = E_{Material\ extraction_i} + E_{Material\ process_i} + E_{Manufacturing_i} + E_{Reman_i} \quad (3.4)$$

$$Energy\_Recoverd_{\ Shred/Rc_i} = E_{Material\ extraction_i} + E_{Material\ process_i} + E_{Shredding/Recycling_i} \quad (3.5)$$

$$Economic\ Profit = RS + CC + \sum_{i \in reman} Eco\_Cost_{Reman_i} \ * X_{i1}$$

$$Recovered\ energy \ = (\sum_{i \in reman} Energy\_Recovered_{Reman_i} * X_{i1} + \sum_{i \in Shred/Rc} Energy\_Recoverd_{\ Shred/Rc_i} * X_{i2})/E_{\ total} \quad (3.7)$$

Subject to:

$$\sum_i (X_{i1} + X_{i2} + X_{i3} + X_{i4} + X_{i5}) = 1,\ X_{i1}, X_{i2}, X_{i3}, X_{i4}, X_{i5} = 1\ or\ 0 \quad (3.8)$$

For subcomponent i that belongs to assembly k:

If $X_{k1} + X_{k2} + X_{k3} + X_{k5} = 1; \quad then \quad X_{i5} = 1$ (3.9)

If $X_{k4} = 1; \quad then \quad X_{i1} + X_{i2} + X_{i3} = 1$ (3.10)

where

C_{Reman_i}: remanufacturing cost of component i, which can be estimated from the multiple of labor cost and the total time required for remanufacturing component i, which includes sorting, cleaning, reconditioning and testing process;

$C_{Miscellaneous_i}$: cost of handling, disassembly, storage, reassembly of component i;

$C_{Shredding/Recycling_i}$: shredding/recycling cost of component i, which can be estimated from the scrap value of the materials times the weight of material;

$C_{Newpart_i}$: replacement cost of component i;

$C_{Landfill_i}$: landfill cost of component i, which can be estimated from the landfill cost times the weight of material;

$\mathrm{E}_{Material\ extraction_i}$: energy required to extract the raw material to produce component i;

$\mathrm{E}_{Material\ process_i}$: energy required to process the material to produce component i;

$\mathrm{E}_{Manufacturing_i}$: energy required to manufacture component i;

E_{Reman_i}: energy required to remanufacture component i;

$\mathrm{E}_{Shredding/Recycling_i}$: energy required to shred/recycle component i;

RS: product resale price;

CC: product collection cost;

DS_k: disassembly cost of assembly k;

E_{total}: energy required to produce the product, including material extraction energy, material processing energy and manufacturing energy

Solving these multi-objective functions requires a discrete optimization algorithm due to their combinatorial nature. As simple enumeration is computationally too expensive even for simple products with relatively small number of components, the Non-Dominated Sorting Generic Algorithm-II (NSGA-II) is chosen to approximate the optimum trade-off solutions between the economic profit and recovered energy rapidly. In NSGA-II, the chromosomes are codified in the forms of a string consisting of (N+M) genes, where N and M represent the number of the subassemblies and components respectively. The value of each gene can be integer value from 1 to 5, which represent five different EOL options, namely remanufactured, shredded/recycled, landfilled, disassembled, and remains within the parent assembly. The implementation details for NSGA-II can be found in Deb et al. (2002).

Stage IV: multi-situational analysis and redesign suggestions

The result obtained from NSGA-II is a Pareto set of trade-off solutions between economic profit and environmental impact, subject to the three constraints presented. As the Pareto sets of EOL solutions can be generated within a reasonable time, the algorithm thus permits extensive sensitivity analysis to understand thoroughly the impact of situational variables, such as landfill cost, labor cost, collection cost, remanufacturing capability, on EOL decision making (Pareto frontier). Meanwhile, redesign ideas or solutions can be tested and verified efficiently, so as to promote better EOL strategy planning and product development.

3.1.3 Case Studies

To illustrate the proposed methodology, two types of EOL desktop phones have been chosen, namely a normal consumer desktop phone and a business IP desktop phone. Desktop phone remanufacturing can be dated backed to more than 50 years ago, aiming to give a second life to the used and defective desktop phone equipment. Recently, manufacturers and producers of desktop phones are also given the greater responsibility under the Waste Electrical and Electronic Equipment (WEEE) Directive for the collection, recovery or recycling of the e-waste that their goods become, if they produce electrical and electronic equipment or import them into Europe. Due to the limited information available, it is assumed that both desktop phones and their components have fulfilled the remanufacturing feasibility requirements, implying that steps I and II of the decision support tool will not be included in this case study. This assumption will be further examined in the next section through sensitivity analysis to address the uncertainties that may be involved. The economic information as well as the bill of material of the desktop phones were taken from Johnson (2002), which includes, product resale price, part remanufacturing cost, disassembly/reassembly cost, shredding/recycling cost, new part cost, landfill cost for each subassembly/component. For environmental impact analyses, the following data and assumptions are adopted:

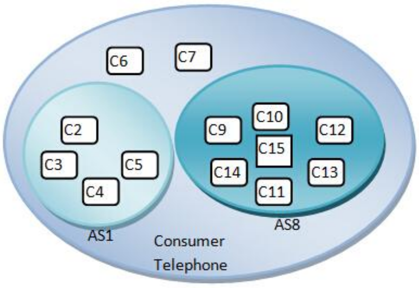
1) Energy consumption for material extraction and processing is approximated by the embodied energy of materials. The database for material embodied energy is taken from Curlee et al. (1994).

2) As the energy intensity of conventional manufacturing processes for metals, plastics and many composites falls roughly within the range of 1-30 MJ/Kg, the manufacturing energy intensity for each component is assumed to be 15 MJ/kg (Duque Ciceri et al., 2010). For electronic components, which have relatively high energy intensity, the method to estimate their manufacturing energy will be adopted from Ashby (2012) and Kemna et al. (2005).
3) Energy consumption of a remanufacturing process can be expressed through the ratio of remanufacturing energy consumption to the original manufacturing energy consumption. Usually, the ratio ranges between 2% and 25%, subject to

different conditions (Sutherland et al., 2008). In this case, the value 25% will be taken to make a conservative estimate of energy saving through remanufacturing.

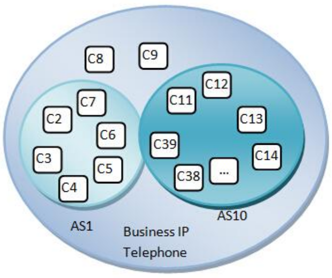
4) The energy required to re-process the materials at their EOL stage is called "secondary material production energy". The estimated values of the secondary production energy for different materials are provided by Curlee et al. (1994) and Sullivan and Hu (1995).

Figures 3.2 and 3.3 show the graphical representation of both types of phones. Using the cost information, bill of material as well as the energy consumption data, the EOL economic and environmental profits for each subassembly and component are calculated and shown in Tables 3.1 and 3.2. Taking the energy recovered through remanufacturing for component C2 of consumer telephone as an example, the value is calculated as the sum of the material extraction and processing energy (7652.46 KJ), manufacturing energy (1455.00KJ) and remanufacturing energy (-363.75 KJ). These values will be used as input for the optimization model to calculate the optimum set of EOL strategies. The minus infinite sign in Tables 3.1 and 3.2 indicate the infeasible EOL options. To illustrate the implementation of NSGA-II algorithm, the consumer telephone is utilized here as an example. The chromosome will be codified in the form of a string consisting of 15 genes, presenting two assemblies and thirteen subcomponents and each gene can take the value from 1 to 5. The initial population consists of 1000 random chromosomes that satisfy constraints described in Equations 3.8-3.10. For example, if Assembly#1 is assigned to be recycled, all of its subcomponents 2, 3, 4, 5, should remain within Assembly#1. Once the populations are initialized, they will be sorted based on nondomination into different fronts using the economic and environmental objectives stated in equation 3.6 and 3.7. Based on sorting result, the best populations will be selected to generate the offspring populations, using the uniform crossover and multiple point mutations. After that, the populations with the current populations and current offspring will be sorted again. To achieve an efficient convergence to a high-quality Pareto curve, the algorithm will run through 200 loops. This technique is proven to be very effective in finding a wide spread of economic and environmental Pareto solutions for both cases, as shown in Figure 3.4, Figure 3.5, Table 3.3 and Table 3.4.



AS1: Handset; C2: Upper Phone; C3: lower Phone; C4: Electrical Subassembly; C5: Speaker; C6: Electric cord 1; C7: Electric Cord 2; AS 8: Phone base; C9: Upper Shell; C10: Circuit Board; C11: Al casting1; C12: Al casting 2; C13: Silence switch; C14: Hang up switch; C15: Lower Shell

Figure 3.2: Graphical representation of consumer telephone



AS1: Handset; C2: Upper Handset; C3: Lower Handset; C4: Handset Circuit Board; C5: Connector; C6: Receiver; C7: Microphone Assembly; C8: Electrical Cord 1; C9: Electrical Cord 2; AS10: Telephone base; C11: Upper Plastic Casing; C12: Speaker Foam; C13:4 Screws; C14: Speaker; C15: Plastic Plate; C16: PolyFlex Circuit Board; C17: LCD Panel#1-Subassembly; C18: Main Circuit Board; C19: Elastomer Key Pad#1; C20: Elastomer Key Pad#2; C21: Elastomer Key Pad#3; C22: Shift Button; C23: 12 Memory keys; C24: 3 Display Buttons; C25: Feature Buttons; C26: Release button; C27 Hold Button; C28: 12 Dial Keys; C29: 12 Line Keys; C30: Volume Control; C31:Display Cover-LCD#1; C32: Display Cover-LCD#2; C33: LCD Panel #2; C34: Hang Up Level; C35:Metal Clip; C36: Lower Plastic Casing; C37: 2 Rubber Pads; C38: Plastic Stand; C39: 2 Rubber Pads

Figure 3.3: Graphical representation of business IP telephone

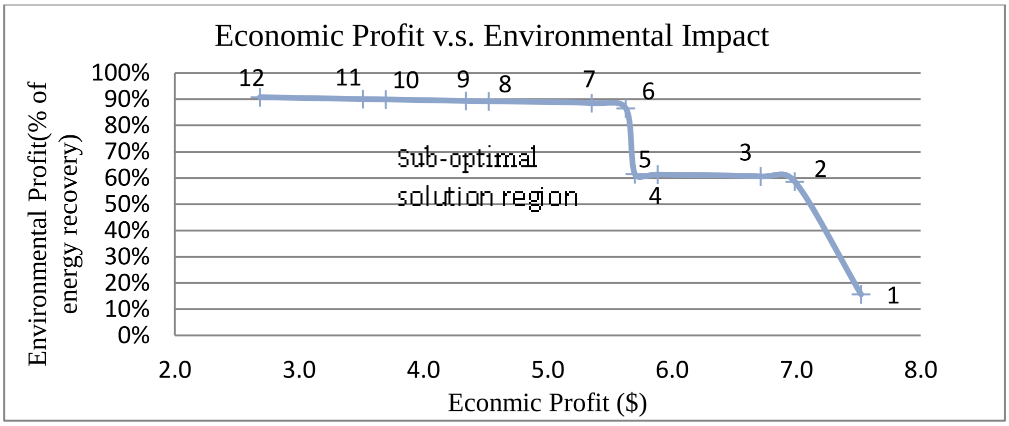


Figure 3.4: Optimal EOL strategy set for consumer telephone

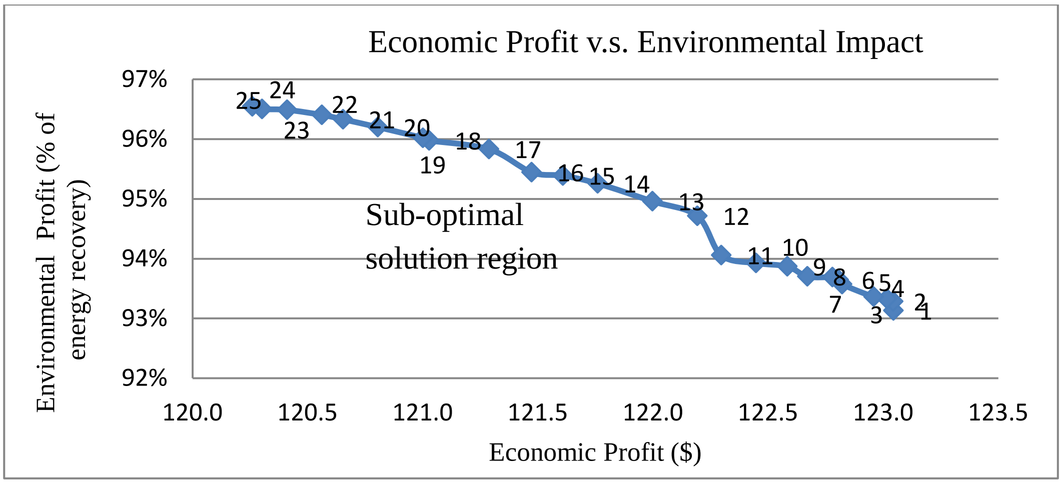


Figure 3.5: Part of optimal EOL strategy set for business IP telephone

Table 3.1: Economic and environmental data for consumer telephone

Name	Eco_Reman ($)	Eco_Shrd/Rc ($)	Eco_Lf ($)	Eco_Dis ($)	Evn_Reman (KJ)	Evn_Shrd/Rc (KJ)
AS1	-∞	-∞	-3.12	-0.167	0.00	0.00
C2	-0.85	-1.13	-1.13	-∞	8743.71	2666.27
C3	-0.76	-1.23	-1.22	-∞	8743.71	2666.27
C4	-1.44	-0.43	-0.52	-∞	4214.28	2384.60
C5	-0.12	-0.18	-0.20	-∞	7532.68	4557.02
C6	-1.04	-0.22	-0.24	-∞	5066.73	3032.55
C7	-1.09	-0.26	-0.28	-∞	5066.73	3032.55
AS8	-∞	-∞	-4.68	-1.25	0.00	0.00
C9	-0.84	-0.90	-0.91	-∞	26377.38	7330.56
C10	-2.47	-1.11	-1.21	-∞	81130.16	19495.48
C11	-0.17	-0.32	-0.37	-∞	9099.62	5230.17
C12	-0.17	-0.32	-0.37	-∞	9099.62	5230.17

C13	-0.49	-∞	-0.22	-∞	4388.73	0.00
C14	-0.33	-0.41	-0.41	-∞	3510.98	1004.82
C15	-1.12	-∞	-1.14	-∞	26332.38	0.00

Table 3.2: Economic and environmental data for business IP telephone

Name	Eco_Reman ($)	Eco_Shrd/Rc ($)	Eco_Lf ($)	Eco_Dis ($)	Evn_Reman (KJ)	Evn_Shrd/Rc (KJ)
AS1	-∞	-∞	-3.90	-1.99	0.00	0.00
C2	-0.20	-0.76	-0.76	-∞	6502.15	1860.74
C3	-0.20	-0.76	-0.76	-∞	6119.65	1751.41
C4	-0.74	-0.77	-0.80	-∞	1432.90	1130.85
C5	-0.47	-0.39	-0.39	-∞	655.55	398.64
C6	-0.11	-∞	-0.16	-∞	566.42	0.00
C7	-0.42	-∞	-0.22	-∞	96.49	0.00
C8	-1.04	-0.22	-0.24	-∞	4544.81	3007.55
C9	-1.08	-0.26	-0.27	-∞	2897.78	1916.82
AS10	-∞	-∞	-29.35	-0.66	0.00	0.00
C11	-0.18	-2.57	-2.56	-∞	18731.10	5360.74
C12	-0.08	-0.14	-0.14	-∞	538.39	286.79
C13	-0.44	-0.41	-0.42	-∞	188.04	139.91
C14	-0.56	-0.98	-0.99	-∞	6045.80	4590.42
C15	-0.20	-0.20	-0.20	-∞	1986.50	1817.75
C16	-1.14	-∞	-3.92	-∞	742.05	0.00
C17	-1.24	-∞	-5.39	-∞	1765.27	0.00
C18	-4.06	-4.35	-4.35	-∞	4037.28	3186.39
C19	-0.20	-0.45	-0.45	-∞	2239.01	1493.59
C20	-0.20	-0.51	-0.51	-∞	1253.98	836.50
C21	-0.20	-0.55	-0.55	-∞	1121.98	748.44
C22	-0.23	-0.07	-0.07	-∞	43.89	12.56
C23	-0.23	-0.22	-0.22	-∞	1456.77	867.36
C24	-0.23	-0.07	-0.07	-∞	357.58	212.90
C25	-0.23	-0.07	-0.07	-∞	131.67	37.68
C26	-0.23	-0.07	-0.07	-∞	87.77	25.12
C27	-0.23	-0.27	-0.27	-∞	87.77	25.12
C28	-0.23	-0.40	-0.40	-∞	570.54	163.28
C29	-0.23	-0.22	-0.22	-∞	781.20	223.57
C30	-0.23	-0.09	-0.09	-∞	87.77	25.12
C31	-0.16	-0.23	-0.23	-∞	623.32	367.81
C32	-0.20	-0.48	-0.48	-∞	465.02	274.40
C33	-1.23	-∞	-0.85	-∞	392.77	0.00
C34	-0.24	-0.70	-0.70	-∞	359.88	102.99
C35	-0.07	-0.52	-0.52	-∞	105.30	64.05
C36	-0.18	-1.25	-1.26	-∞	26701.04	7641.69
C37	-0.15	-∞	-0.55	-∞	379.50	0.00
C38	-0.18	-0.90	-0.91	-∞	12016.35	3439.01
C39	-0.15	-∞	-0.55	-∞	379.50	0.00

Table 3.3: Optimum EOL strategy set for consumer telephone

Comp / Solution	AS 1	C 2	C 3	C 4	C 5	C 6	C 7	AS 8	C 9	C 10	C 11	C 12	C 13	C 14	C 15
1	4	1	1	2	1	2	2	3	5	5	5	5	5	5	5
2	4	1	1	2	1	2	2	4	1	2	1	1	3	1	1
3	4	1	1	2	1	2	2	4	1	2	1	1	1	1	1
4	4	1	1	2	1	2	1	4	1	2	1	1	1	1	1
5	4	1	1	1	1	2	2	4	1	2	1	1	1	1	1
6	4	1	1	2	1	2	2	4	1	1	1	1	3	1	1
7	4	1	1	2	1	2	2	4	1	1	1	1	1	1	1
8	4	1	1	2	1	1	2	4	1	1	1	1	1	1	1
9	4	1	1	1	1	2	2	4	1	1	1	1	1	1	1
10	4	1	1	2	1	1	1	4	1	1	1	1	1	1	1
11	4	1	1	1	1	1	2	4	1	1	1	1	1	1	1
12	4	1	1	1	1	1	1	4	1	1	1	1	1	1	1

1: remanufacturing; 2: shredding/recycling; 3: landfill; 4: disassemble; 5 remain within assembly

Table 3.4: Part of optimum EOL strategy set for business IP telephone

Sol \ Comp	AS 1	C2	C3	C4	C5	C6	C7	C8	C9	AS 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26	C 27	C 28	C 29	C 30	C 31	C 32	C 33	C 34	C 35	C 36	C 37	C 38	C 39
1	4	1	1	1	2	1	3	2	2	4	1	1	2	1	2	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
2	4	1	1	1	2	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
3	4	1	1	1	2	1	3	2	2	4	1	1	1	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
4	4	1	1	1	1	1	3	2	2	4	1	1	2	1	2	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
5	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	1	1	1	3	1	1	1	1	1	1
6	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
7	4	1	1	1	1	1	3	2	2	4	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
8	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	3	1	1	1	1	1	1
9	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	1	1	1	1	1	1	1
10	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
11	4	1	1	1	1	1	3	2	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
12	4	1	1	1	2	1	3	1	2	4	1	1	1	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
13	4	1	1	1	1	1	3	1	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	1	1	1	3	1	1	1	1	1	1
14	4	1	1	1	1	1	3	1	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	1	1	1	1	1	1	1
15	4	1	1	1	1	1	3	1	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	2	1	1	1	1	1	1	1	1	1
16	4	1	1	1	1	1	3	1	2	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
17	4	1	1	1	1	1	3	1	1	4	1	1	1	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	3	1	1	1	1	1	1
18	4	1	1	1	1	1	3	1	1	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	3	1	1	1	1	1	1
19	4	1	1	1	1	1	3	1	1	4	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	3	1	1	1	1	1	1
20	4	1	1	1	1	1	3	1	1	4	1	1	2	1	1	1	1	1	1	1	1	2	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
21	4	1	1	1	1	1	3	1	1	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
22	4	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	1	1	1	2	1	1	1	1	1	1	1	1	1
23	4	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1
24	4	1	1	1	1	1	1	1	1	4	1	1	2	1	1	1	1	1	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1
25	4	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1

1: remanufacturing; 2: shredding/recycling; 3: landfill; 4: disassemble; 5 remain within assembly

3.1.4 Results and Discussion

Steps I and II of the decision support tool provide a systematic process to evaluate the feasibility of a product and its components for remanufacturing. As described earlier, the evaluation process comprises a sequential examination of characteristics that define the prerequisites for carrying out product or part remanufacturing. Failing to fulfill one or more of the prerequisites will mean that the external conditions would be working against the product or part remanufacturing efforts. In addition, the sequential examination process aims to stimulate process modification or product redesign in the case where a product or a component is not feasible for remanufacturing. For example, if technical data required to restore a product is not available while the product has been returned for remanufacturing, reverse engineering can be carried out to extract the needed technical data. Another example is to improve the design viability of a product or subassembly through decoupling the design elements that will suffer early obsolescence from the more stable product systems and thus extend the product valuable lifetime.

In the third step, the EOL strategy planning is optimized with respect to two objectives, namely, maximizing economic benefit and minimizing environmental impact. As shown in Figures 3.4 and 3.5, each point on the Pareto curve represents an optimal EOL strategy between cost and environmental cautious actions. Moving along the Pareto line from the rightmost strategy to the leftmost strategy, the economic return decreases with an increase in energy recovery rate. Using Figure 3.4 as an example, Strategy#1 on the curve is the maximum profit strategy with the lowest energy recovered rate, which involves complete disassembly of Assembly#1 and landfilling Assembly#8 as a whole unit; Strategy#12, located on the other extreme, corresponds to the maximum energy recovered strategy with the lowest economic return, which suggests complete disassembly of the product and remanufactures every single component. The business IP telephone remanufacturing has shown both economic and environmental advantages over the consumer telephone remanufacturing; at the maximum profit strategy, 86% of the embodied energy of the business telephone can be preserved, whereas for the consumer telephone, only 15% of the product energy can be retained.

It would not be difficult to notice the two abrupt kinks on the Pareto curve of Figure 3.4, which involve 43% and 25% increase in the energy recover rate at Strategy#2 and Strategy#6. On a closer examination, some redesign ideas may be inspired, such as incorporating design elements to facilitate the disassembly of Assembly#8; or redesigning component#10 with elements to facilitate its upgrade, replacement or other forms of enhancement. These redesign ideas can be re-run with the optimization model to examine their impact on EOL recovery strategy. For example, as shown in Figure 3.6, the shape of the Pareto curve has changed along with the decrease in the disassembly cost of AS8. The "tipping scenario" happens when the disassembly cost of AS8 drops below 50%. In this scenario, the EOL strategy of AS8 will change from landfill to disassembly with all of its components remanufactured, recycled or disposed of.

The EOL strategy planning process can be rather complex and dynamic in the real world. Factors, such as the value and cost of components, replacement parts availability, technology availability, are not stable and will affect the EOL decision making to various degrees. To address the complexity of EOL decision making, sensitivity analysis with respect to different situational variables can be carried out to understand their impact on EOL Pareto solutions.

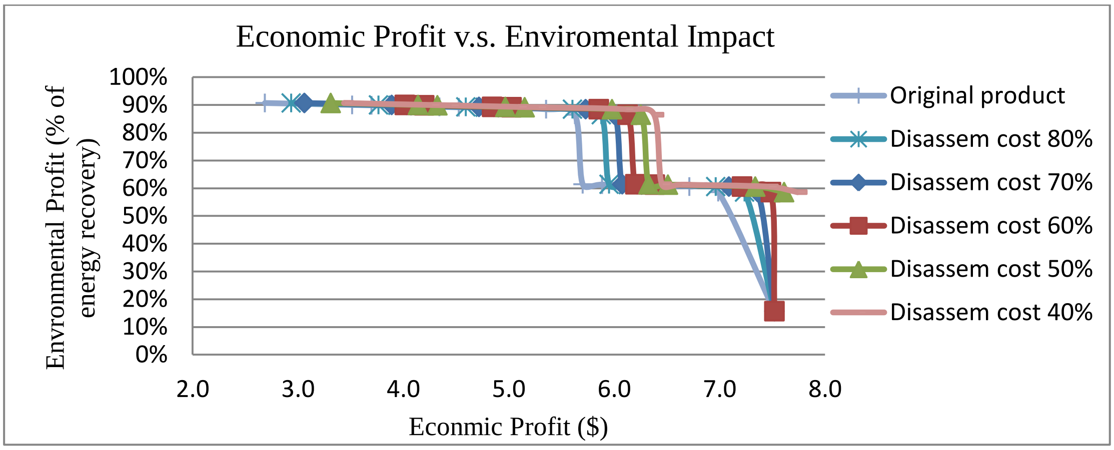


Figure 3.6: Impact of design change of consumer telephone on Pareto set

Figure 3.7 illustrates the multi-situational strategy graphs constructed for the business IP phone case study. The trade-off sets are provided for the base case along with four other scenarios featuring differences in replacement part availability, labor cost, transportation and collection cost, landfill cost. The results have provided significant insights regarding the impact of these situational factors on EOL decisions. For example, the addition of the transportation and collection cost will cause a parallel shift of the Pareto curve, as the incurred cost is applied on the product level. The change of labor cost will affect the remanufacturing cost of each component and thus incur the noticeable change of the shape of the Pareto curve. The replacement parts availability and remanufacturing technology availability can affect the EOL choices and thus the overall remanufacturing strategies. For example, when replacement parts for C8 and C9 are not available, the returned parts will need to be remanufactured. Comparing with other scenarios, the Pareto curve is less affected by the change of landfill cost in this case study, as most of the components are planned to be remanufactured or shredded/recycled.

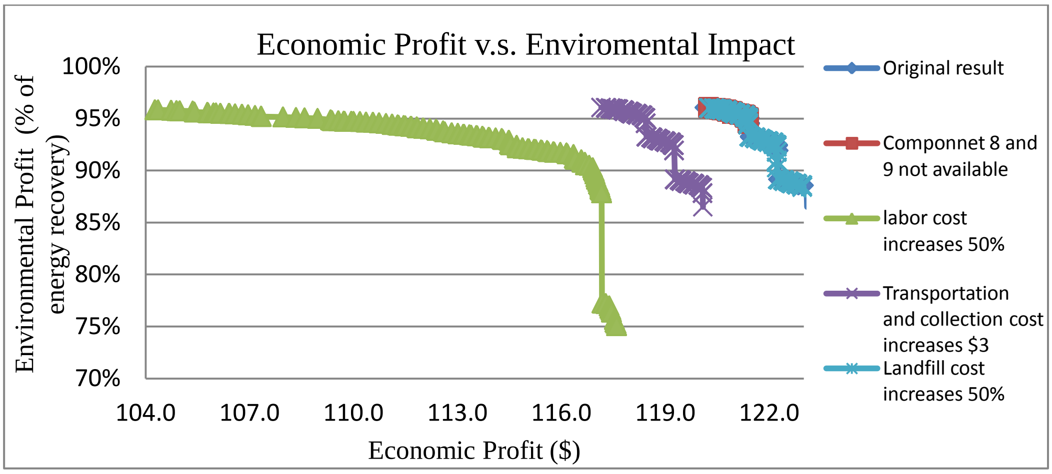


Figure 3.7: Multi-situational EOL strategy graph for business IP telephone

The applicability of the proposed methodology has been demonstrated using relatively simple desktop phones. However, it can handle products with a large number of components due to the efficiency and effectiveness of NSGA-II to identify optimal EOL solutions in a large search space. The foreseeable limitation may come from data acquisitions for the input of this methodology, which includes the remanufacturing cost and the replacement cost of each component, and the disassembly and reassembly costs. This limitation can be addressed by relating to similar product EOL information or consulting with remanufacturing experts for a reasonable estimation. Other information, such as material recycling value, landfill cost, embodied energy, secondary production energy, can be stored in the data base. Once the product information, such as Bill of Materials, has been keyed in, the economic and environmental profit can be calculated automatically, to reduce the burden of data acquisition. Meanwhile, it is noted that the economic profit and environmental impact are the two objectives optimized in this study, and to capture other dimensions of considerations, such as production cost, product performance, additional metrics can be added to the objective functions as the NSGA-based methodology is general in dimensionality and can be utilized for establishing Pareto sets, which consider trade-offs between more than two metrics simultaneously. Therefore, the proposed methodology can serve to accelerate the diffusion of remanufacturing requirements into original product design requirements by providing an approach that decision makers can use to quantify and visualize the trade-offs between requirements from different disciplines.

In addition, the proposed optimization model deals with the economic performance of one product type in a decoupled way, i.e., without considering the financial synergy resulted from sharing reverse logistic cost or setup cost with other products types within the factory. When a full-scale treatment of economic analysis is carried out, the proposed methodology can be iterated with the readjusted cost value, such as the reverse logistic cost or resale price, in order to recalculate the EOL strategy on the single-product level.

3.1.5 Summary

A decision support tool to facilitate product remanufacturing strategy planning is presented in this section. This methodology has advanced the previous research in EOL decision planning in the following three features, Firstly, the proposed methodology provides a holistic approach, where a four-step decision tool will guide decision makers towards optimum EOL strategies decisions, through addressing the comprehensive aspects of remanufacturing considerations; Secondly, the methodology provides flexibility by utilizing NSGA-II to determine explicitly a Pareto set of optimal EOL solutions to facilitate the effort of the decision makers to maximize the environmental benefit of remanufacturing for a given economic profit. Lastly, the methodology is comprehensive as the Pareto sets of optimum solutions can be calculated within a reasonable computational time, which permits extensive sensitivity analysis to understand the impact of situational variables on EOL decision making thoroughly, and thus leading to the improved EOL decision making and product design. The applicability of NSGA-II for determining the Pareto set of optimal EOL solutions has been demonstrated numerically with two desktop phones case studies.

3.2 Design for Remanufacturing

3.2.1 Introduction

Besides assessing the remanufacturability of the products and components at the early design stage, the proposed research will take a proactive measure to improve the potential of the product for remanufacturing, through developing an effective and efficient product design support tool. As 80% of the cost of the product is determined at the design stage, it is of significance to address the remanufacturing issue and concern during this stage (David et al., 2014). Previous research has presented a comprehensive design for remanufacturing guidelines to address and mitigate the difficulty involved in each remanufacturing steps, like design for disassembly, design for cleaning, design for reconditioning, etc. Being required to consider each remanufacturing aspect individually may be the most effective method, but in reality may be an overly daunting and time consuming task for the designers. Most of the design guidelines for remanufacturing are fairly general in descriptions and rarely consider how these design aids may fit in with the already-sophisticated design process (Hatcher et al., 2011). Meanwhile, it is a widely recognized belief that DfRem is most effective when implemented in the early design stage, as few decisions have been made and the design freedom is large (Amezquita et al., 1995; Zwolinski et al., 2006). However, many of the DfRem tools being proposed by academia, especially those of quantitative nature require too much technical data and thus either are too complex to be used at the early design stage or by the time product specification has been defined, are too late to make substantial changes to the design (Hatcher et al., 2011). In addition to this, design for remanufacturing should not be considered in an isolated manner. Given the potential conflict that DfRem may have with other DfX methodology, such as assembly and manufacture, there is a need for an analysis that can demonstrate properly how and to what degree DfRem has an impact on the remanufacturing process and other life cycle stages that are involved (Zwolinski et al., 2006).

To address the above mentioned limitations, a holistic decision support tool for DfRem is developed and presented in this section. 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 to address various aspects of remanufacturing concerns. While these four aspects are only a subset of product design considerations, they are selected because they are particularly relevant to the realization of remanufacturing objective. The design for remanufacturing requirement or criteria will be presented firstly in a manner that designers are familiar with to reduce the complexity of the design process. After that a decision support tool based on multi-criteria decision making technique, namely

Fuzzy Technique of ranking Preferences by Similarity to the Ideal Solution (Fuzzy TOPSIS) has been presented to evaluate the impact of DfRem on remanufacturing efficiency. The selected design alternatives will further be compared in a proposed multiple life cycle assessment model to examine the impact of remanufacturability enhancement design features on overall life cycle performance, so as to improve the effectiveness and robustness of the decision change. In addition, to assist decision makers in the application of the proposed methodology and to simplify computation complexity, a computation tool based on the Visual C# has been developed, which allows for fast computation and ease of use of this methodology. The applicability of the decision support tool will be demonstrated using automotive parts design.

3.2.2 Major DfRem Considerations

Materials selection is at the core of decision-making throughout product design development, as the material properties can influence the various aspects of product life cycle, such as manufacturing cost, market acceptance, functional performance (Andrea and Brown, 1993). The product remanufacturing performance, including component recoverability, economic incentive, the amount and toxicity of the waste generated through remanufacturing, etc., is also largely influenced by the properties of the materials used (Charter and Gray, 2008). To facilitate the remanufacturing process, it is desirable for the materials of the product to be durable so as to enhance the service life of the components and prevent the core from breaking down during remanufacturing. Meanwhile, it is desirable that properties of the materials are adaptable to cleaning and reconditioning process.

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 also 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 (Amezquita et al., 1995; Ijomah et al., 2007; Sundin and Lindahl, 2008). When the products are disassembled for remanufacturing, there are usually three types of scenarios planned for its joints/fasteners and adjoining parts. The first scenario is disassembly without destruction, including joints/fasteners. In this scenario, adjoining parts are intended for reuse and/or remanufacturing and the condition of the joints/fasteners after disassembly is also important. The second scenario is disassembly without destruction, excluding joints/fasteners. In this situation, disassembly without any degradation to adjoining parts is desired, in order to be reused for remanufacturing. However, the condition of the joints/fasteners after disassembly is not critical and thus the joints/fasteners are allowed to be destructed if necessary. The third scenario is disassembly with allowable destruction. This would be in a recycling context, where the separation of the parts is important, yet damage to those parts and joints/fasteners is acceptable. Given the three different EOL scenarios for the adjoining parts, it is critical that the decision makers prioritize the EOL scenarios and rate the performance of the candidate joining methods towards each scenario accordingly. Besides, the cost and the environmental consideration should also be accounted during the joining methods selection process.

Another design aspect which is closely related to product remanufacturing efficiency is product structure design. Product remanufacturing, especially in complex product remanufacturing, is a challenging task as it involves the disassembly process to separate different materials and retrieve the reusable components in a non-destructive and cost-effective manner, which is closely related to the way the components are arranged and interacted upon in the product (Kuo, 2006; Chu et al., 2009). Meanwhile, the number, design tolerance, shape and position of components will also affect the efficiency of various remanufacturing processes, such as cleaning, inspection, reconditioning. For example, if the part to be replaced is located deeply inside a product, accessing and retrieving the part becomes challenging and could increase the cost of remanufacturing. Or if the number and types of components of the product is large, it will increase the complexity of component discerning and classification as well as the possibility of selecting wrong components when performing reassembly.

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 and it may not possess the desirable surface properties, surface coating will be applied to the substrate to meet certain surface requirements, such as surface fatigue resistance, wear, corrosion, or for aesthetic purposes. 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 (Sundin and Lindahl, 2008). Thus the selection of the surface coating should account for the environment in which a component will face and the degradation factors that may cause component failure, in order to enhance the product durability performance, meanwhile facilitate the cleaning and restoration process that core will go through.

The detailed remanufacturing evaluation criteria with respect to these four design aspects are compiled and presented in Table 3.5. It is noted that the design considerations, presented in Table 3.5, are meant to be applied to the components or parts that have been identified to have the potential for remanufacturing, especially those components which have high embedded value, long technology life-cycle or high durability, e.g., engine, turbocharger, starter, alternator, etc.. Meanwhile, it may not be sensible to be applied to the situations where there is an industry standard for certain design requirement.

Table 3.5 : Evaluation criteria 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	• Ease of removing impurity and deposit	• 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	• Standardization of joining method	• 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 (EHS)	• Recyclability • Air emissions and waste disposal • Toxicity • Scarcity of raw material • Law and regulation	• Compatibility with other parts • Toxicity	• Recyclability	• Air emissions and waste disposal • Recyclability • Law and regulation
Cost	• Raw material cost	• Labor cost • Capital 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	• Compatibility with substrate material

3.2.3 Evaluating the Impact of DfRem on Remanufacturing Performance

The proposed criteria and consideration can either be used as a guideline to assist the product designer at the early stage, or to be used to as a set of criteria for evaluating the impact of alternative design features on product remanufacturability. An optimal selection from a finite set of feasible alternatives and predetermined number of criteria is often regarded as a multi-criteria decision making (MCDM) problem. Among these MCDM methods, Fuzzy TOPSIS is chosen in this research to evaluate the design concepts with respect to their performance on the remanufacturing process, and aims to enable designers to make better design choices and enhance the opportunity for product remanufacturing. The performance of different design concept or choices, like material selection, material joining method, structure design and surface coating, will be evaluated based on the remanufacturing considerations, including durability, cleanability, restorability and upgradability, EHS, cost and complexity, as presented in Table 3.5. This is a research area that has not been explored previously, but deserves attention due to the environmental and economic benefits that can be achieved through automotive remanufacturing as well as the impact of initial product design on product remanufacturability. The framework of this decision support tool is presented next.

Step 1: Determining the candidate components for remanufacturing

The proposed decision support system is meant to be applied to the components or parts that have been identified to have the potential for remanufacturing. However, during the remanufacturing process, it is unlikely that all the components of the returned products will be remanufactured. The detailed guideline for identifying the candidate product and its components for remanufacturing can be found in section 3.1.

Step 2: Selecting the evaluation aspect and design candidates

The set of remanufacturing evaluation metrics with respect to material selection, material joining method, structure design and surface coating are compiled and shown in Table 3.5. Decision makers will need to select the design aspect they want to examine and select the feasible design candidates for evaluation and comparison.

Step 3: Building performance matrix

The performance of candidate materials against the evaluation criteria is collected from the SAMSG (Sustainable Automotive Materials Selection Guide) (NCMS, 2012), the material handbooks (Bauccio, 1993; Davis, 1996; Murray, 1997), website information (Guesser 2004; Dawson and Indra, 2012), as well as the remanufacturing experts, who have over 25 years of remanufacturing working/research experience. The variable r_{ij} is used to represent the performance rating of ith material alternative with respect to jth evaluation criterion and the material performance matrix R is thus expressed as Equation 3.11, where X_1 ... X_m are the design candidate and $A_1 \ldots A_n$ are the evaluation criteria.

$$
\begin{array}{cc} & \begin{array}{ccccc} X_1 & \cdot\cdot & X_i & \cdot\cdot & X_m \end{array} \\
R = \begin{array}{c} A_1 \\ \vdots \\ A_j \\ \vdots \\ A_n \end{array} & \begin{bmatrix} r_{11} & \cdots & r_{i1} & \cdots & r_{m1} \\ \vdots & & \vdots & & \vdots \\ r_{1j} & \cdots & r_{ij} & \cdots & r_{mj} \\ \vdots & & \vdots & & \vdots \\ r_{1n} & \cdots & r_{in} & \cdots & r_{mn} \end{bmatrix} \end{array} \qquad (3.11)
$$

Step 4: Calculating the weight factor

As a product or component will be used in different application environments by different end users, and has different design restrictions, the design evaluation criteria are usually not of equal importance relative to each other. Therefore, some forms of weighting shall be introduced as part of the evaluation process. In order to obtain a more reasonable weight coefficient, the weight w_j for the *j*th criterion will be a combination of two sets of weights, as shown in Equation 3.12, where α_j is the weight obtained via the entropy method (Shannon and Weaver, 1947) and β_j is the subjective weight assigned by experts from the remanufacturing field. In Equation 3.12, *j* is the number of the criterion and *n* is the total number of criteria.

$$w_j = \frac{\alpha_j * \beta_j}{\sum_{j=1}^{n} \alpha_j * \beta_j} \quad j = 1, \dots, n \tag{3.12}$$

a) The set of weight from the entropy method:

The entropy method makes use of the information that is already contained in the defined material performance matrix R and uses the probability theory to derive directly the relative importance of the evaluation criteria. The underlying principle is to assess the uncertainty in the information, as there is a common agreement that a broader distribution represents a greater uncertainty than that of a sharply peaked one (Shanon and Weaver, 1947). This method consists of following procedures.

(1) Normalization of the decision matrix R.

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \qquad i = 1,2, \dots, m; \ j = 1, 2, \dots, n; \tag{3.13}$$

In Equation 3.13, *i* is the number of the alternative, *m* is the total number of alternatives and P_{ij} represents the normalized performance matrix.

(2) Calculate the Entropy E_j of the normalized values of jth criterion.

$$E_j = -(\frac{1}{\log(m)}) \sum_{i=1}^{m} P_{ij} \log(P_{ij}) \quad i=1,2,\ldots, m; j=1, 2,\ldots, n; \qquad (3.14)$$

The calculated value of the Entropy E_j will be in the range of [0-1].

(3) Calculate the weight α_j of the Entropy of jth criterion

$$\alpha_j = \frac{|1-E_j|}{\sum_{j=1}^{n}|1-E_j|} \qquad j=1, 2,\ldots, n; \qquad (3.15)$$

If P_{ij} for jth criterion has wide range, it will yield a small value of E_j, which will result in the large weight factor α_j.

b) Subjective weight from expert's input

The subjective weight is assigned by experts from the remanufacturing field based on their professional judgment and past experience, which is a simplified way of weight determination and reduces the computational time and complexity. A numerical approximation system is used to convert the linguistic judgment systematically to their corresponding crisp score, as shown in Table 3.6.

Table 3.6: Crisp value for subjective importance rating

Rating of relative importance	Very low (VL)	Low (L)	Medium (M)	High(H)	Very high (VH)
Crisp value	1	3	5	7	9

Step 5: Developing ranking for design candidates using the Fuzzy TOPSIS method

Despite its effectiveness in concept, TOPSIS is often criticized for its inability to deal with the vagueness and uncertainty involved in the judgment process. Hence, the fuzzy set theory is proposed to be combined with the TOPSIS method, which is also known as the Fuzzy-TOPSIS approach. This combined approach can handle the imprecise information by converting them into linguistic variables, which will be expressed using a triangular fuzzy number, i.e., $[a_{ij}m_{ij}, b_{ij}]$, as illustrated in Table 3.7. In this way, a higher degree of uncertainty can be included in the decision making process.

According to the concept of the TOPSIS, the relative closeness value C_i^+ is introduced to determine the ranking order of the alternatives, by calculating the distance of the alternative to the ideal solution, namely S_i^+ and its distance to the non-ideal solution, namely S_i^-. The larger the closeness value, the better is the design alternative. In the fuzzy environment, the distance between two triangular fuzzy numbers will be calculated using a vortex method. Detailed calculation steps for carrying out Fuzzy-TOPSIS can be referred to Chen's work (2000) and Wang and Chan's work (2013).

Table 3.7: Linguistic rating r_{ij} and its corresponding crispy value and triangular fuzzy number

Rating of design performance	Poor (P)	Medium poor (MP)	Fair (F)	Medium good (MG)	Good (G)
Fuzzy number	[0,1,3]	[1,3,5]	[3,5,7]	[5,7,9]	[7,9,10]

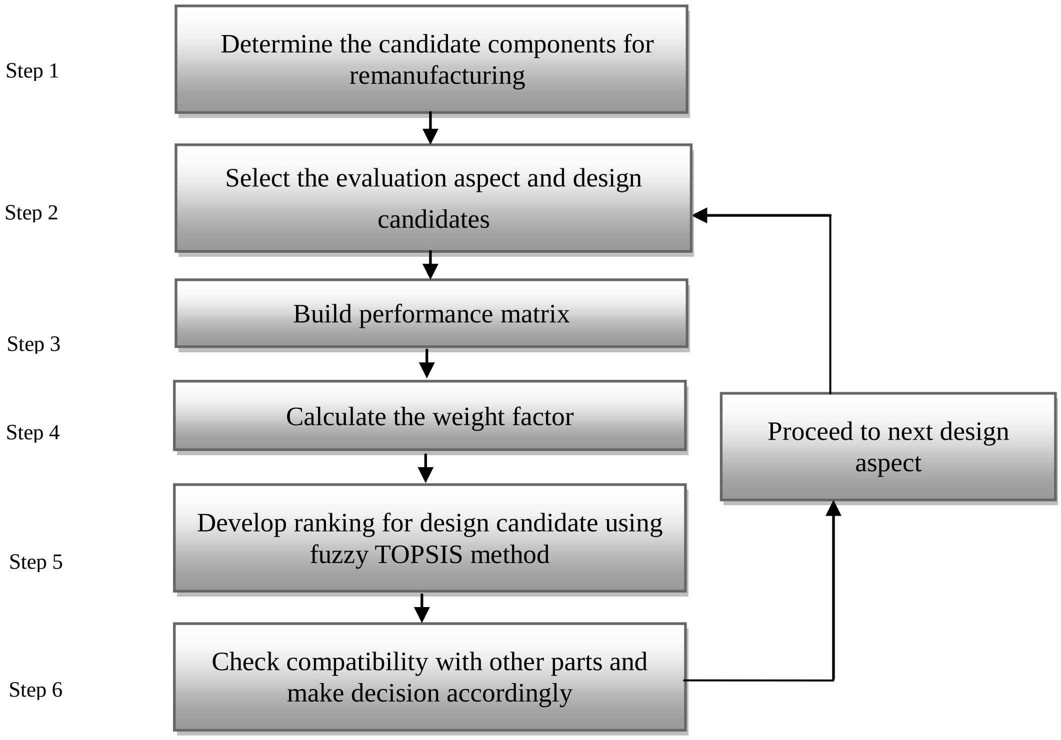


Figure 3.8: Flow chart for the proposed decision support tool

Step 6: Compatibility check

Once the ranking for the design candidate for the designed part has been obtained, decision makers may proceed with product internal check to detect whether there are any potential conflicts with design choices or design constraints of other parts, such as different coefficient of thermal expansion between the neighboring components or decrease in functional performance. If the selected design candidate for the designed component may lead to constraints in the options available for other element, the next optimum design candidate will be chosen. A flow chart of the proposed methodology for designing automotive products for remanufacturing is shown in Figure 3.8.

3.2.4 Evaluating the Impact of DfRem on Product Life Cycles

Product design for remanufacturing cannot be viewed in an isolated manner, as mentioned by several researchers (Shu and Flowers, 1999; Ijomah et al., 2007) that DfRem is often in conflict with other DfX methodology, such as manufacturing and environment. A guideline which can assess the impact of remanufacturability enhancement features on the overall product life cycle and delivers a robust and comprehensive remanufacturing design suggestion is of great importance. To address this need, a decision support tool is proposed, which incorporates the "life cycle think" to evaluate the economic and environmental impact of remanufacture enhance features over multiple usage cycles. Meanwhile, the situational variables, such as successful remanufacturing rate and number of life cycles, will be accounted in the model to examine their impact on the overall life cycle performance.

The traditional "cradle-to-grave" product life cycle has been adapted to "cradle-to-cradle", as graphically represented in Figure 3.9. Basically, six generic phases, namely material extraction and processing (MEP), manufacturing (MA), transportation (TR), usage stage (US), product take back (PTB), and remanufacturing (RE), have been included to describe the life-cycle of a product. The method assumes that the number of products within a system is N, and the first use cycle will be composed of the newly manufactured products only. During the remanufacturing stage, $\mu * N$ cores will be reprocessed to "good as new" quality to enter into the next life-cycle, while the lost cores will be made up with $(1-\mu) * N$ virgin products.

Cumulated Energy Demand (CED) will be used to represent the sum of the primary energy demand throughout the life span of a product, and thus approximates the holistic environmental performance of remanufacturing enhancement features. To apply the concept of CED to the above described life-cycle model, CED will be 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 3.16

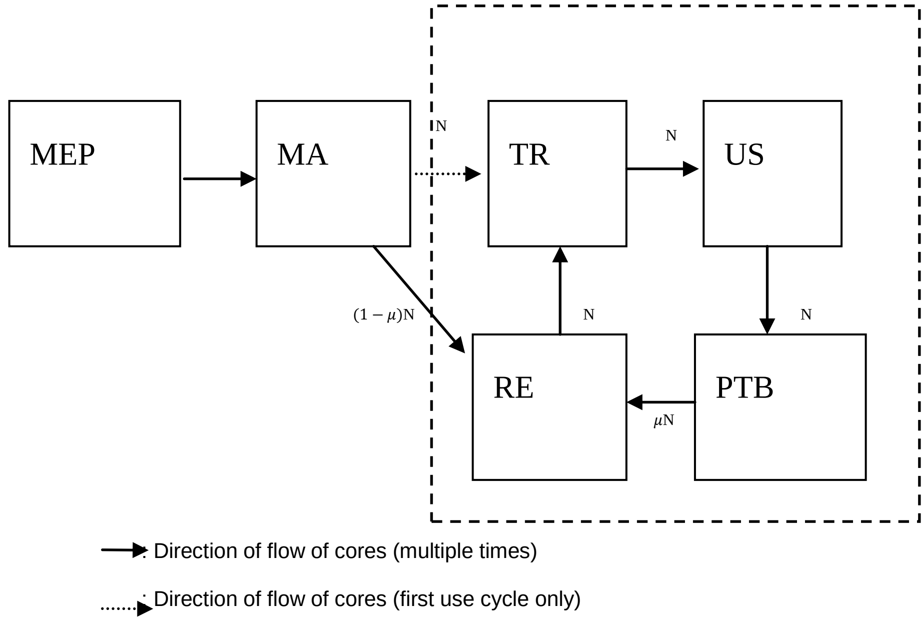


Figure 3.9: Flow of products over multiple life-cycles

Similarly Cumulated Cost (CC) will be used to represent the sum of the expense throughout the life span of a product and its mathematical expression is shown in Equation 3.17.

$$CED_{Total} = CED_{MEP_1} + CED_{MA_1} + \sum_{i=1}^{M} \left(CED_{US_i} + CED_{TR_i} + CED_{PTB_i} \right)$$

$$+ \sum_{i=2}^{M} \left(\mu_i * CED_{RE_i} + (1-\mu_i) * \left(CED_{MA_i} + CED_{MEP_i} \right) \right) \quad (3.16)$$

$$CC_{Total} = CC_{MEP_1} + CC_{MA_1} + \sum_{i=1}^{M} \left(CC_{US_i} + CC_{TR_i} + CC_{PTB_i} \right)$$

$$+ \sum_{i=2}^{M} \left(\mu_i * CC_{RE_i} + (1-\mu_i) * \left(CC_{MA_i} + CC_{MEP_i} \right) \right) \quad (3.17)$$

where:

M : number of life-cycles;

μ : successful remanufacturing rate;

i : i^{th} life cycle;

CED_{Total} : CED throughout the entire product life span;

CC_{Total} : CC throughout the entire product life span;

CED_{MEP_i} : CED for the material extraction and processing during i^{th} life cycle;

CC_{MEP_i} : CC for the material extraction and processing during i^{th} life cycle;

CED_{MA_i} : CED for the product manufacturing during i^{th} life cycle;

CC_{MA_i} : CC for the product manufacturing during i^{th} life cycle;

CED_{TR_i} : CED for the transportation of product during i^{th} life cycle;

CC_{TR_i} : CC for the transportation of product during i^{th} life cycle;

CED_{US_i} : CED for the use of product during i^{th} life cycle;

CC_{US_i} : CC for the use of product during i^{th} life cycle;

CED_{PTB_i} : CED for the take-back of product during i^{th} life cycle;

CC_{PTB_i} : CC for the take-back of product during i^{th} life cycle;

CED_{RE_i} : CED for the product remanufacturing during i^{th} life cycle.

CC_{RE_i} : CC for the product remanufacturing during i^{th} life cycle.

It should be noted that for a complex life cycle that involves product remanufacturing, designers have to estimate the maximum number of life-cycles M that a product or component can support. During the remanufacturing process, it is unlikely that 100% of the product can be remanufactured successfully to "good as new" quality due to recovery process capability (poor quality of returned cores, technology constrains, low recoverable value etc.). Hence, an estimation of the successful remanufacturing rate is required. Further, only the remanufacturing strategy is considered as the closed-loop strategy, as it is the main focus of this study and is able to preserve more significant amount of embedded energy of the product than other closed-loop strategies. The inclusion of other recovery strategies, such as recycling or disposal, will be addressed in the future study.

3.2.5 Overall Approach for Product Design for Remanufacturing and its Software Implementation

The DRRA tool is built based on the following four steps, which are illustrated graphically in Figure 3.10.

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.

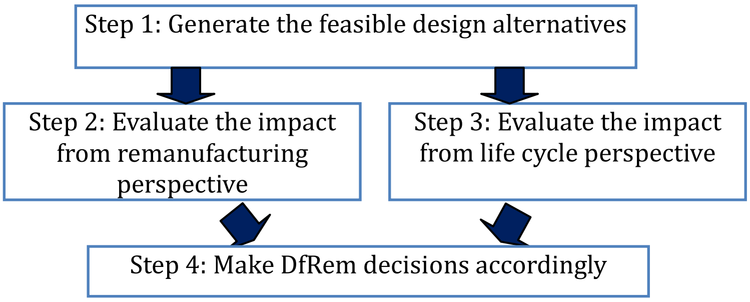


Figure 3.10: Flowchart for the proposed DfRem approach

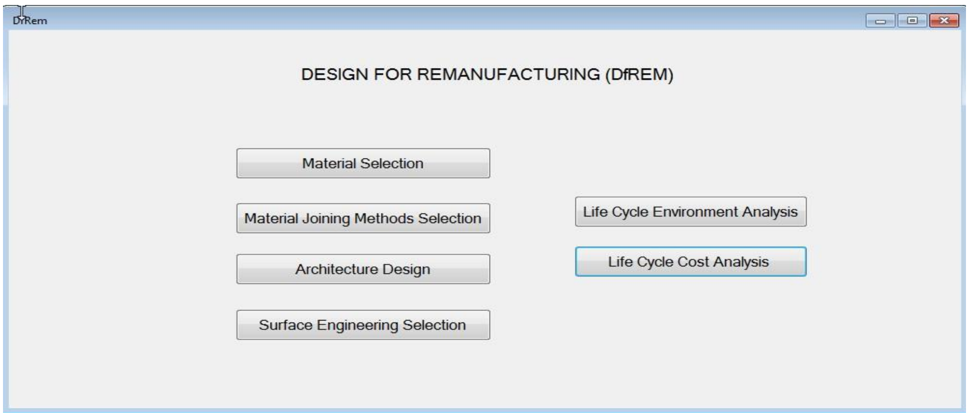


Figure 3.11: Screenshot of DfRem support tool

In order to assist decision makers in the application of the proposed methodology and to simplify computation complexity, a computation tool based on the Visual C# has been developed, which allows for fast computation and ease of use of this design aid. With this approach, decision-makers can obtain the impact of remanufacturing design features on both remanufacturing performance as well as overall product life cycle, thus to improve the effectiveness and robustness of the decision making and encourage greater incorporation of the remanufacturability concept during the product design stage. A screenshot of the program is shown in Figure 3.11. The screenshots for the sub-functions are shown in appendix IV.

3.2.6 Case Study I

In the following two sections, an engine block and an alternator have been selected to examine the applicability of the proposed design for remanufacturing support tool. The aim is to examine suitable design that can enhance the remanufacturability, meanwhile improve the overall life cycle environmental performance.

Engine block is the core of the engine, which houses nearly all the components required for the engine to function properly. Many engine blocks in the early stage are manufactured from cast iron alloy due to its high strength and low cost. However, as engine designs become more complicated and heavier, some manufacturers have started to use lighter alloys, such as aluminum alloy, of which the density ratio to cast iron is 0.37 only. Due to relatively lower tensile strength and damping capacity of aluminum, such a design change may require a greater volume of aluminum to achieve a comparable functional performance of cast iron. Nevertheless, experience with practical substitution of cast iron with aluminum indicates that 1 kg of aluminum can replace up to 2 kg of cast iron for automotive product design (Vatsayan et al., 2014). Most recently, newly developed material processing technology has made Compacted Graphite Iron (CGI) viable alternative to grey cast iron for engine blocks. Therefore, in this case study, three different types of materials, namely, Grey Cast Iron ASTMA48 Class 40, Aluminum A356-t6 and CGI ASTM A482 Grade 450, are selected and their impact on remanufacturing efficiency and life cycle performance will be examined next.

To evaluate the impact of design alternatives on the remanufacturing efficiency, the methodology proposed in section 3.2.3 will be adopted. The performance rating of these materials with respect to the six evaluation aspects and the subjective weights for each of the evaluation criteria are collected and shown in Table 3.8. Using the Fuzzy TOPSIS method, the ranking of the candidate materials in terms of their remanufacturability, are calculated and shown in Table 3.10.

Further, to evaluate the design alternatives from the life cycle perspective, the design information as well as the estimated functional and EOL performance of the three design alternatives, as collected and presented in Table 3.9 (Adler et al., 2007; Vartabedian, 1992; Dawson and Indra, 2007; Sahni et al., 2010, Smith and Keoleian, 2004). Detailed information, assumption and calculation can also be found in Yang et al’s (2014b). The parameters for energy intensity, such as embodied energy intensity, manufacturing energy intensity, remanufacturing energy intensity are stored in the design tool database, which would automate and speed up the calculation process (Koffler and Rohde-Brandenburger, 2010; Boustead and Hancock, 1979; Smith and Keoleian, 2004; Smil, 2008; Sutherland et al., 2008);

To demonstrate the environmental benefits of the design alternatives over complex life-cycles, the energy consumption of aluminium and CGI engine block, relative to cast iron engine block will be evaluated. The result of the environmental performance for the design alternatives using equation 3.16, is shown in Figure 3.12 and the breakdown of energy consumption is shown in Figure 3.13.

Table 3.8: Candidate materials for Engine Blocks and their performance ratings

CRITERIA	Importance	Grey Cast Iron ASTMA48 Class 40	Aluminum A356-t6	CGI ASTM A482 Grade 450
Durability	High	Medium Good	Fair	Good
Cleanability	High	Medium Good	Fair	Medium Good
Restorability	Very high	Medium Good	Fair	Fair
EHS	Medium	Good	Medium good	Good
Cost	High	Good	Fair	Good
Complexity	N.A.	N.A.	N.A.	N.A.

Table 3.9 : Specifications, Functional and EOL performance of design alternatives

	 **Cast Iron Engine Block**	 **Aluminum Engine Block**	 **CGI Engine Block**
Material	Grey Cast Iron ASTMA48	Aluminium A356-t6	CGI ASTM A482 Grade 450
Mass (kg)	158 kg	130 kg	134 kg
Life mileage (km)	1,200,000km	1,200,000km	1,200,000km
Functional performance	Equivalent	Equivalent	Equivalent
Reman rate (%)	60%	50%	70%

Table 3.10 : Relative closeness and ranking of each candidate material

	Relative closeness	Ranking
Grey Cast Iron ASTMA48	0.82	2
Aluminum A356-t6	0.01	3
CGI ASTM A482 Grade 450	0.89	1

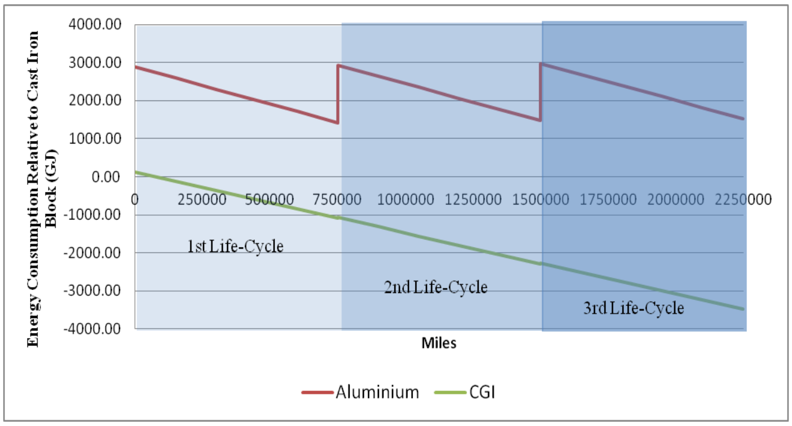


Figure 3.12: Engine blocks life cycle environmental performance

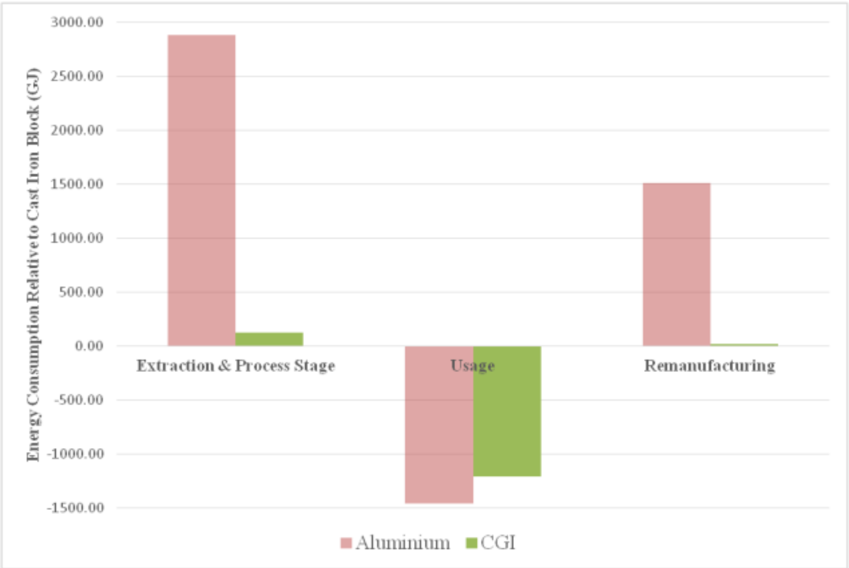


Figure 3.13: Engine blocks energy consumption breakdown

3.2.7 Case Study II

In this case study, the design evaluation was carried out for three alternative alternators designs. The parts which feature the difference in three alternator design are shown in Table 3.11 (Schau et al., 2012). To evaluate their impact on the remanufacturing process, three design alternatives are assessed using the evaluation criteria proposed in this framework. The performance rating of the three types of alternators are shown in Table 3.12 and the calculated remanufacturing performance ranking are presented in Table 3.13.

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 are shown in Table 3.11 and Table 3.14, which will be used as the input for the proposed design support tool. In this case, Design #I will be used as the reference to calculate the relative energy consumption of the other two design alternatives. The results of the study are shown in Figure 3.15 and Figure 3.16

Table 3.11: 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 3.12: 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 3.13: 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 3.14: Functional and EOL performance of design alternatives

	Design #I	Design #II	Design #III
Life mileage (km)	200,000km	200,000km	200,000km
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%

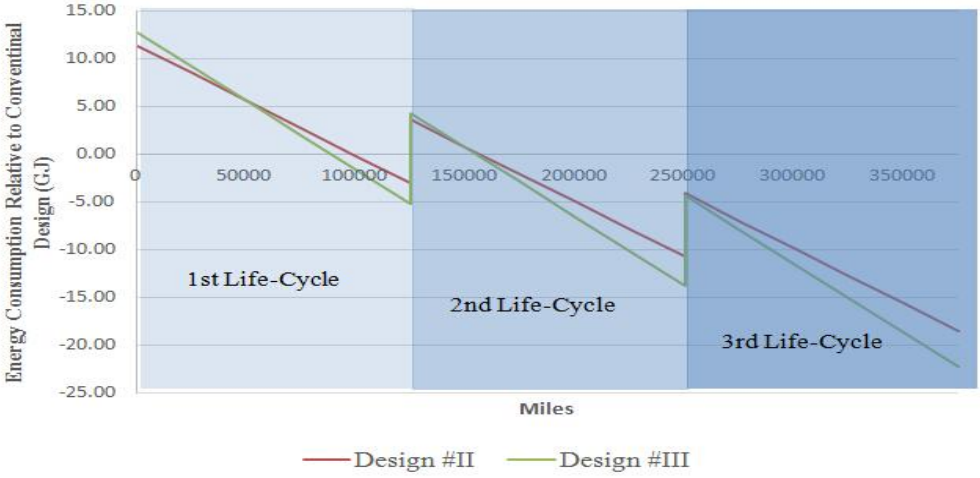


Figure 3.14: Alternators environmental performance

Figure 3.15: Alternators energy consumption breakdown

3.2.8 Results and Discussion

In the first case study, Compact Graphite Iron and Grey Cast Iron are ranked as the better material choices from the perspective of remanufacturing due to their desirable performance in wear resistance, fatigue resistance and reliability, which are the key enablers for successful engine block remanufacturing. Although Aluminum demonstrates superior performance in “Density”, it is a criterion considered less critical for product remanufacturability, thus leading to relatively lower rankings for Aluminum. As from the life cycle environmental analysis, CGI engine block appears superior to Aluminum and Cast Iron engine blocks due to its relatively light weight design and satisfactory remanufacturing rate. Although the Aluminum block design is the lightest among all the alternatives, it is comparatively more energy intensive to produce and remanufacture as observed in Figure 3.13, which overwhelms the benefits obtained from weight reduction energy savings.

In the second case study, Design#I is ranked as the best candidate from the remanufacturing perspective, due to its desirable performance on durability, cleanability and restorability, and hence it 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 Figure 3.15.

The results of these case studies have highlighted the issue of using light duty materials in automotive design. Original equipment manufacturers tend to use lighter duty materials, such as Aluminum or plastics, to reduce weight and subsequently improve the product performance (e.g., fuel efficiency and CO_2 emissions) during the use stage. However, this tends to make parts more fragile and/or prone to breakage during remanufacturing processes, and thus reduces the number of remanufacturing cycles of the parts. In addition, failure due to the use of light duty material during the use stage often results in catastrophic destruction of components, which reduces the possibility of remanufacturing substantially. This issue has been addressed previously in a survey conducted in the automotive industry (Hammond et al., 1998) and is now validated quantitatively in this research. Moreover, it is known that many lightweight materials, e.g., aluminum, magnesium or polymer composite, are considerably more energy-intensive to produce than, for example, conventional cast iron, prior to the use stage (Koffler and Rohde-Brandenburger, 2010). Hence, whether the light weight design strategy is beneficial depends 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. Therefore, a model which can estimate the overall environmental trade-offs of the different design concepts accurately within complex life cycles is of significance. The proposed tool has provided an easy-to-use and effective approach to support this analysis.

Further, the results obtained for these two case studies are dependent on the underlying assumptions and data, among which, the successful remanufacturing rate, weight-induced fuel saving rate, life mileage and product life span are of major importance. To examine the impact of these situational variables on the results obtained, a sensitivity analysis can be carried out. For example, sensitivity analysis indicates that the Aluminum engine block would need a successful remanufacturing rate of 90% for two life-cycles in order to achieve a better environmental performance than cast iron engine block. Decision makers can adjust the value of the situational variables based on different constraints they faced and make decisions on the product design accordingly. Moreover, it is noted that the present studies have assumed the equality of the functional performance of the design alternatives in the use phase; future studies can account for the energy saving that might be induced by the changing of functional performance of design alternatives.

The case studies discussed in this chapter illustrate the impact of the selection of materials on both remanufacturing process and life cycle performance. Other design considerations, as discussed in section 3.2.2, can also be evaluated and compared in the similar fashion. To automate the evaluation process and ease the decision making, a knowledge database has been built and integrated with the DfRem software tool. For example, the performance values of different joining methods on remanufacturability evaluation criteria have been stored in the database, which can be recommended and auto-populated in the entry boxes to save user input, thus to improve the effectiveness the DfRem tool.

Recognizing the greatest impact of design stage on EOL possibility, the research topic of design for remanufacturing has received relatively generous amount of attention over the recent years, yet in reality, the increase in DfRem activity has yet to be realized proportionally. Therefore, factors that may affect the integration and implementation of DfRem, like management support, cross functional communication, market demand, remanufacturing related education and training, shall be investigated properly (Hatcher et al., 2011). This part of the work can be referred to author's work on "Towards implementation of DfRem into the product development process" (Yang et al., 2014a).

3.2.9 Summary

To facilitate the DfRem implementation, a holistic decision support tool is proposed in this section to steer a product design towards higher remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating. The impact of remanufacturability enhancement design features on both remanufacturing performance and overall product life cycle performance can be examined using the proposed MCDM methodology and CED/CC analysis respectively, so as to achieve a robust and comprehensive remanufacturing design improvement.

The main contribution of this method 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 the major input for remanufacturing impact analysis. Meanwhile the life cycle thinking is incorporated in the evaluation scheme, which further improves the effectiveness and robustness of the DfRem decision tool. Moreover, the methodology has demonstrated quantitatively the issue of using light duty materials in automotive design for remanufacturing and highlighted the importance of design decision making from a life-cycle perspective, which should include not only the manufacturing and use stage, but also the EOL disposition.

3.3 Summary of the chapter

This chapter has discussed the approach to assess the feasibility of the product and its components for remanufacturing, meanwhile presented a holistic design support tool to improve the potential of the product for remanufacturing during product development stage. As mentioned previously, nearly 80% of the product cost is committed by the end of the product design stage, it is critical that the proposed remanufacturing activities in this chapter are carried out carefully and timely, if OEMs plan to incorporate remanufacturing as a part of their product life cycle. Through the proposed methodologies, the preliminary ideas of EOL fate of the product/components can be obtained, which will sever as necessary information to facilitate product remanufacturing decision making. Meanwhile, to fit in with the already sophisticated design process, the proposed design tool analyzes the "over-daunting" designs for remanufacturing guidelines and reorganizes them into four major design aspects, namely material selection, material joining methods, structure design and surface coating, that designers are familiar with, so as to reduce the burden of design for remanufacturing. Moreover, life cycle thinking has also been incorporated into the design support tool, aiming to deliver a robust and comprehensive design decision. These features have enabled proposed methodologies to be used effectively during early design stage.

4. END OF LIFE STAGE

Besides the early product development stage, the DRRA tool is also developed to be used during product EOL stage, to assess the suitability of the returned products and especially its components for remanufacture. The question of whether the product or component should be remanufactured depends on various considerations. This question has further been complicated by the uncertainty of the product return conditions. In this regard, a holistic decision support tool which includes both qualitative and quantitative analyses to address the operational and technological considerations for product remanufacturing and optimizes the environmental and economic performance under quality uncertainty is proposed.

4.1 Introduction

With the increasing emphasis on environmental issues recently, treatment of end-of-life (EOL) products is gaining attention. Even though a number of publications on EOL determination and remanufacturability assessment have been identified, there are still some limitations from the following aspects. Firstly, most of the research works assume a single quality grade for core return, ignoring the fact that the quality of the returned cores for remanufacturing is much more uncertain and dynamic than conventional manufacturing (Krikke et al., 1998; Song et al., 2005; Anityasari, 2008; Jin et al., 2011). Secondly, as mentioned earlier, product remanufacturing decision making involves various dimensions of consideration (Goodall et al., 2014; Ziout et al., 2014), and there is still a lack of a holistic approach that can facilitate decision making during the remanufacturing process and ensure the completeness of operational, technological, economic and environmental considerations. Further, the methodology that considers both complete and partial disassembly and optimizes the

EOL decision for each component in a product stewardship system has yet to be fully delineated. These limitations and gaps have constituted to the contributions as well as the motivations of the following research.

In this chapter, a decision support framework for EOL decision making for components of a returned product type is proposed. The framework includes both qualitative and quantitative analyses to address the operational and technological considerations for product remanufacturing, meanwhile optimizing the environmental and economic performance. Probability theory is utilized in the proposed framework to analyze the impact of the quality of the returned products on EOL decision making. In addition, to represent the product structure hierarchy and the interconnections among the components of a product, the Hierarchical Attributed Liaison Graph (HALG) is used, allowing both complete and partial disassembly strategies to be considered during EOL strategy planning.

4.2 Recovery Decision Making for Components of Returned Products

4.2.1 Recovery Strategies Definition

The common EOL strategies include reuse, remanufacturing, recycle, landfill and incineration. Considering that the proposed decision support system is used for companies which main focus is on product remanufacturing, the following EOL strategies will be considered:

Upgrade: The component will be upgraded with the state-of-the-art technology to improve its performance or quality on par with the latest standards, so as to meet the market demand.

Restore: The component will be returned to "as good as new" conditions. The options of upgrade and restore are mutually exclusive.

Disposal: The component will be disposed of and replaced with a new component; material which has recovery value will be recycled and the rest of the material will be incinerated or landfilled.

4.2.2 HALG for Product Structure Representation

The HALG (Dong et al., 2006) is used to represent the product structure hierarchy of the returned products; it can represent the interconnections of the components and subassemblies, which leads to the ease of considering partial disassembly during the disassembly process. In a HALG, the squares and discs represent the subassemblies and components respectively, and the arcs represent the connections between components and subassemblies. Figure 4.1 shows the HALG representation for an automotive alternator, where 0: Alternator; 11: Pulley; 12: Front case; 13: Subassembly 1; 14: Subassembly 2; 21: Rotor; 22: Fan; 23: Subassembly 3; 24: Subassembly 4; 25: Rectifier; 31: Brush; 32: Regulator; 33: Back case; and 34: Stator. Hence, the alternator comprises four levels, four subassemblies and nine components. For each subassembly, there can be different disassembly strategies, which can produce two types of components, namely, *Independent component*, where all the joints connected to that component are disconnected, and the *Connected component*, where there are remaining joints on that component.

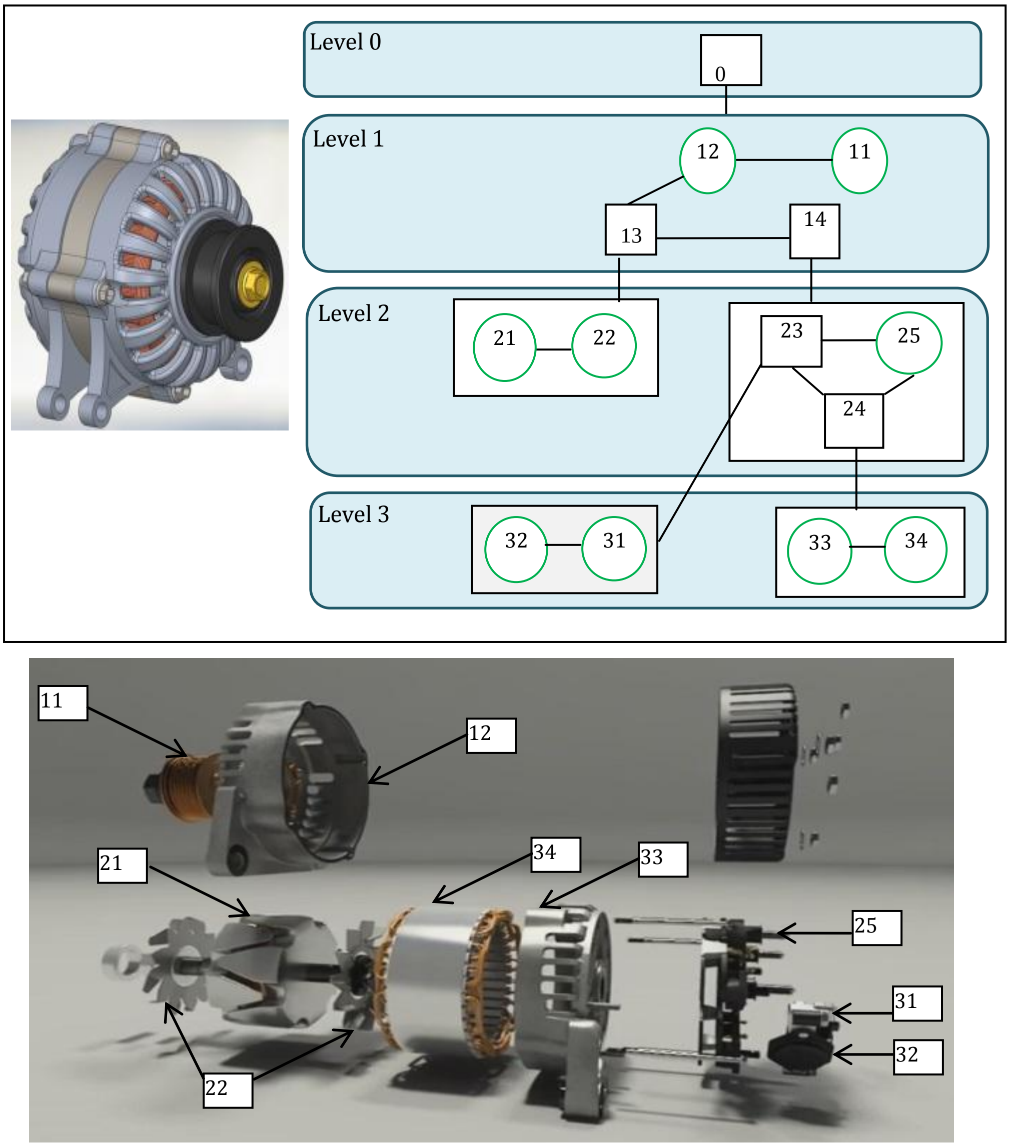


Figure 4.1: HALG representation for an alternator

4.2.3 Operational and Technological Assessments

The objectives of the operational and technological assessments are to remove the subassemblies or components that are obviously non-reusable and classify the reusable subassemblies and components into different quality levels. These assessments consist of the following three steps.

Step 1: A visual and physical inspection is conducted to identify severely damaged and worn items and discard them, e.g., subassemblies that are severely worn, components that are usually replaced, etc. This process can vary among the types of cores being inspected, and is usually performed manually without any tools or instruments.

Step 2: This step estimates the demand of the components and subassemblies. Components and subassemblies that have no demand will be disposed of at this stage. The estimated demand and information of the components and subassemblies allows inventory to be managed for future use.

Step 3: This step assesses the functional performance and assigns a quality level to a subassembly or component. The returned cores usually have varying quality levels. The product quality standards are usually set by the Original Equipment Manufacturers (OEM), international standards or remanufacturing firms. Based on these standards, the quality of the components will be examined and graded. Besides identifying the quality level for each subassembly or component, a subassembly or component that has been tested to be non-reusable will be discarded.

In this framework, the focus is not on the specific mechanisms for quality inspection in these steps as they often vary among the remanufacturers. It is the assessment that must be carried out and the quality levels identified from the technical assessments which are of interest to this methodology.

4.2.4 Conditional Probability of Quality and Expected Profit

The quality of the returned products influences the recovery strategy and it has been identified that remanufacturing cost decreases as the quality increases (Ferguson et al., 2009). In this research, for the purpose of simplicity, two quality levels will be used, namely, 'good conditions' (q=1) or 'malfunctioning' (q=2).

During a disassembly process, there is uncertainty of the quality of the released components and subassemblies. This uncertainty is modelled and defined as a conditional probability Pr_{ij} (q1|q2), which represents the probability of the quality of its subcomponent *i* equals to q1, given the quality level q2 of assembly *j*.

Assuming $C_{i+1,j}$ represents the components released from subassembly SA_{ij} and $PF(C_{i+1,j},q_{i+1,j})$ represents the profit of each component $C_{i+1,j}$ under quality level $q_{i+1,j}$, by using the concept of conditional probability of the quality level, the expected profit $PF(SA_{ij},q_{ij})$ for processing the subassembly SA_{ij} with quality level $q_{i,j}$ is calculated using Equation 4.1, where DC_{ij} represents the disassembly cost associated with subassembly SA_{ij}.

$$PF(SA_{ij},q_{ij}) = \sum_{C_{i+1,j}} \sum_{q_{i+1,j}} \mathrm{Pr}_{C_{i+1,j}}(q_{i+1,j} \mid q_{ij}) * PF(C_{i+1,j},q_{i+1,j}) - DC_{ij} \quad (4.1)$$

4.2.5 Economic and Environmental Indices

Several objectives can be considered for planning the optimum EOL strategy of a component. In this research, the objective is to maximize the economic performance while minimizing the environmental impact. An economic index and an environmental index will be calculated, where all the variables will be evaluated on a monetary scale, and equal weighting will be assumed for each objective.

The economic effectiveness of remanufacturing is determined by benchmarking with EOL options of disposal and replacing with new components in the context of the OEM remanufacturers. Equation 4.2 is used to calculate the component economic index. The cost of component upgrading or restoring is calculated from the remanufacturing processing cost, and the cost of the disposal option is calculated from the components disposal cost plus the cost of producing or ordering the replaced components. The consideration of replacement cost is of great necessity in a product stewardship system, as part of the replacement cost may either encourage or discourage the remanufacturing decision. For example, if the replacement cost is prohibitively high, component remanufacturing is usually recommended, otherwise replacing the low-cost components with new ones might be more economical.

The environmental impact of remanufacturing is assessed based on material consumption, energy consumption, waste generation and toxicity discharged, which are factors/categories used commonly for analyzing the environmental performance (Smith and Keoleian, 2004). These measurements will be converted into monetary values, so as to be comparable with economic performance calculation. Even though there are other environmental impacts, such as the loss of non-renewable resources, Greenhouse Effect, the impact of these factors are currently not required by laws to be borne by companies, therefore they are excluded in this study. However, the proposed method can be extended by adding any environmental impact factor/category that is required in certain applications. In addition, the environmental impact of the disassembly operations is neglected, since most of the disassembly operations are performed manually. Equation 4.3 shows the calculation of the environmental index.

Thus, the overall index of component ij is calculated using Equation 4.4, which is a summation of the economic and environmental indices.

Economic index: $(EC_{ij}, X_{ij}) = (PC_{ij}, X_{ij}) + (NC_{ij}, X_{ij})$ (4.2)

Environmental index: $(EV_{ij}, X_{ij}) = (RMR_{ij}, X_{ij}) * RMC_{ij} + (EP_{ij}, X_{ij}) * EC$

$$+ (WDP_{ij}, X_{ij}) * WMC_{ij} + (TOX_{ij}, X_{ij}) * TMC_{ij} \quad (4.3)$$

Overall index for component ij is calculated as:

$$PF(C_{ij}, X_{ij}) = (EC_{ij}, X_{ij}) + (EV_{ij}, X_{ij}) \quad (4.4)$$

where

ij: The *j*th component on *i*th level

X_{ij}: Indicator of the EOL strategy of component ij.

X_{ij} =1, if the component ij is to be upgraded;

X_{ij} =2, if the component ij is to be restored;

X_{ij} =3, if the component ij is to be discarded with replacement;

(EC_{ij}, X_{ij}):The economic index of component ij, if EOL option X_{ij} is taken;

(PC_{ij}, X_{ij}) :The cost of restoring or upgrading the component ij (if X_{ij} =1 or X_{ij} =2) or the cost of disposing the component ij (if X_{ij} =3) ($);

(NC_{ij}, X_{ij}) :The cost of producing or ordering the new component ij when X_{ij} =3; otherwise (NC_{ij}, X_{ij}) =0 ($);

(EV_{ij}, X_{ij}) :The environmental index of component ij, if EOL option X_{ij} is taken;

(RMR_{ij}, X_{ij}) :Mass of raw material required for restoring or upgrading the component ij (if X_{ij} =1 or X_{ij} =2) or replacing with a new component ij (if X_{ij} =3) (kg);

RMC_{ij} : Raw material cost ($/kg);

(EP_{ij}, X_{ij}) :Energy required for restoring or upgrading the component ij (if X_{ij} =1 or X_{ij} =2) or disposal and replacing with a new component ij (if X_{ij} =3) (MJ);

EC : Energy cost ($/MJ);

(WDP_{ij}, X_{ij}) :Waste generated for restoring or upgrading component ij (if X_{ij} =1 or X_{ij} =2) or disposing the component ij and replacing with a new component (if X_{ij} =3) (kg);

WMC_{ij}: Waste management cost ($/kg);

(TOX_{ij}, X_{ij}): Toxic discharged during restoring or upgrading of component ij (if X_{ij} =1 or X_{ij} =2) or disposing the component ij and replacing with a new component (if X_{ij} =3) (kg);

WMC_{ij}: Toxicity management cost ($/kg);

$PF(C_{ij}, X_{ij})$: The overall index of component ij, if EOL option X_{ij} is taken.

4.2.6 Overall Approach for EOL Decision Making of Returned Products

An optimum combination of the EOL strategies for the components of a returned product is determined according to the following three steps, which are illustrated in Figure 4.2.

Step 1: Conduct operational and technological assessments (Section 4.2.3: Steps 1 and 2) to identify the subassemblies or components that are non-reusable. Develop the HALG (Section 4.2.2) for the remaining subassemblies and components.

Step 2: Stochastic dynamic programming to determine an optimum EOL strategy for each component by

a) Estimating the overall index for each component for different EOL strategies under different quality levels, according to Equations 4.2 to 4.4 (Section 4.2.5).

b) Starting from the lowest level i (L_i), for each component ij (C_{ij}) and for each quality level (Q_{ij}), choose an EOL strategy $X_o \in X_{ij}$, such that the overall index of component ij is maximum ($MPF(C_{ij}, q_{ij})$), i.e.:

$$\forall C_{ij} \in L_i, \forall q_{ij} \in Qij;\ MPF(C_{ij}, q_{ij}) = \max_{X \in X_{ij}} PF(C_{ij}, q_{ij}, X) \tag{4.5}$$

$$\text{Set } X^{best}(C_{ij,} q_{ij}) = X_0 \tag{4.6}$$

c) If i>1, i=i-1

c1:For each component (C_{ij}) in level i (L_i):

For each quality level (Q_{ij}), choose an EOL strategy $X_o \in X_{ij}$, such that the overall index of component ij is maximum ($MPF(C_{ij}, q_{ij})$), i.e.:

$$\forall C_{ij} \in L_i, \forall q_{ij} \in Q_{ij};\ MPF(C_{ij}, q_{ij}) = \max_{X \in X_{ij}} PF(C_{ij}, q_{ij}, X) \tag{4.7}$$

$$\text{Set } X^{best}(C_{ij,} q_{ij}) = X_0 \tag{4.8}$$

c2:For each subassembly (SA_{ij}) in level (L_i):

Enumerate all the disassembly strategies D_{ij} for SA_{ij}. For each disassembly strategy $d \in D_{ij}$, label the subcomponents ($C_{i+1,j}$) released from SA_{ij} as:

▪**Independent component** ($ID\_C_{i+1,j}$), if all the joints connected to component $C_{i+1,j}$ are disconnected. The maximum overall index of each independent component is equal to the maximum overall index $MPF(C_{ij}, q_{ij})$ calculated from Steps b or c1.

▪**Connected component** ($CN\_C_{i+1,j}$), if there are remaining joints on component $C_{i+1,j}$. The maximum overall index of this group of components is equal to the sum of the indices of disposing these components i.e., $\sum_{CN\_C_{i+1,j}} PF(CN\_C_{i+1,j}, X=3)$ as disposal is the only feasible EOL strategy for these connected components.

Therefore, for each quality level (Q_{ij}), and for each disassembly strategy D_{ij}, choose the disassembly strategy $d_o \in D_{ij}$ such that the overall index of the subassembly SA_{ij} is maximum, i.e.,

$$\forall SA_{ij} \in L_i, \forall q_{ij} \in Q(ij), \forall d \in D_{ij}$$

$$MPF(SA_{ij}, q_{ij}) = \max_{d \in D_{ij}} \{ \sum_{ID\_C_{i+1,j}} \sum_{q_{ID\_C_{i+1,j}}} \Pr_{ID\_C_{i+1,j}}(q_{ID\_C_{i+1,j}} \mid q_{ij})$$

$$* MPF(ID\_C_{i+1,j}, q_{ID\_C_{i+1,j}}) + \sum_{CN\_C_{i+1,j}} PF(CN\_C_{i+1,j}, X=3) - DC(d)\} \quad (4.9)$$

$$\text{Set } d^{best}(SA_{ij}, q_{ij}) = d_0 \quad (4.10)$$

Noted that if d_0 = [∅], the best disassembly strategy is to dispose the subassembly SA_{ij}, as a whole without further disassembly.

d) If i>1, i=i-1, go to Step c, else go to Step e.

e) The stochastic dynamic programming stops at level 0 (product level).

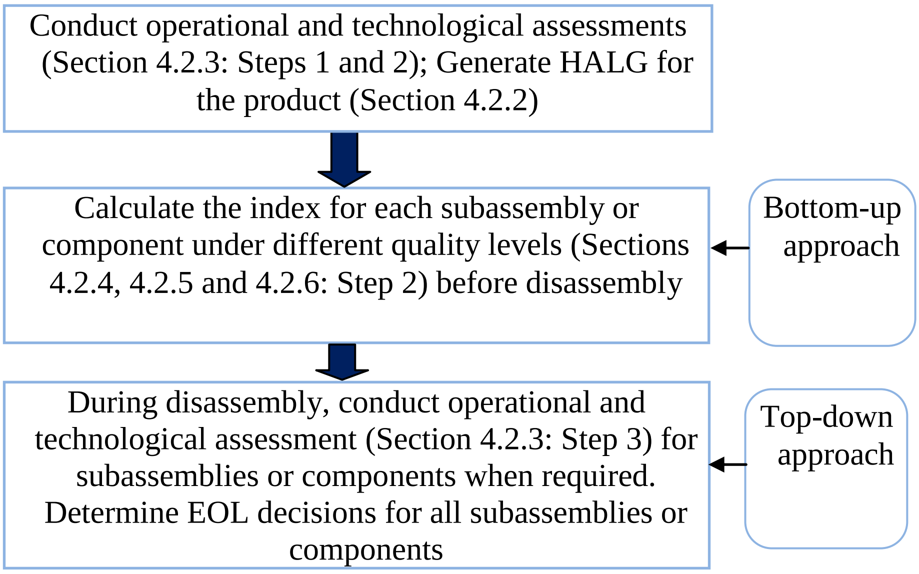


Figure 4.2: Flowchart for the EOL strategy planning

<u>Step 3:</u> During the disassembly process, if the quality level needs to be examined, operational and technological assessments will be performed (Section 4.2.3: Step 3). Otherwise, the optimum EOL options determined in Step 2 will be adopted. The assessment will stop when an EOL option has been determined for each of the components or subassemblies.

4.3 Case Studies

Two case studies have been chosen and conducted to demonstrate the proposed methodology, which are an automotive alternator and a hedge trimmer.

4.3.1 Case Study I

Alternators, which are basic automotive parts, are chosen to illustrate the applicability of the proposed model. Alternators remanufacturing comprises of more than 45% of the revenue in the North American aftermarket and is performed by hundreds of companies in 2005. To apply the proposed methodology for an alternator, firstly the operational and technological assessments are performed to remove components that are non-reusable or frequently replaced, such as washers, screws, springs. After that, the HALG for the remaining components is constructed and shown in Figure 4.1, which enables the users to visualize the hierarchy of the product structure and the interconnections among the components and consequently allowing the partial disassembly strategies to be considered and interpreted during EOL strategy planning.

The required inputs for the model, e.g., economic and environmental index, disassembly cost and conditional probability are estimated and given in Appendices V, VI, VII, VIII (Kim et al., 2008; Schau et al., 2012). The result of applying the proposed methodology (Section 4.2.6) to plan the EOL strategies of an alternator is represented graphically in Figure 4.3. Quality inspection is performed at points which could lead to different EOL decisions. Specifically, quality inspection at the subassembly level, e.g., SA14, would mean that different disassembly strategies might be suggested under different quality states, whereas quality inspection at the component level, e.g., C25, implies that if the quality of the component is good, remanufacturing is recommended, otherwise, disposal and replacing with new component is recommended.

4.3.2 Case Study II

The proposed methodology is further utilized to examine the EOL options for a power tool, i.e., a hedge trimmer, which is remanufactured by some OEM companies, such as Robert Bosch (Atasu et al., 2010). Even in cases where the economics of remanufacturing these products may be marginal (or perhaps negative), there are still several strategic reasons to consider offering these remanufactured products, such as recovering costs from commercial returns, fending off competition from independent third-party competitors, commitment to corporate social responsibility. In order to determine the product structure and component information, a hedge trimmer was disassembled completely. Its HALG was constructed accordingly and shown in Figure 4.4, where 0: Hedge trimmer; 11: Front clamshell; 12: Switch control components; 13: Subassembly 1; 14: Subassembly 2; 21: Subassembly 3; 22: Subassembly 4; 23: Actuator; 24: Back clamshell; 25: Lever; 31: Subassembly 5; 32: Subassembly 6; 33: Blades; 34: Blades Support; 41: Gear case; 42: Gear; 43: Armature & Fan; 44: Brush assembly; 45: Field; 46: Bearing and supports Appendices IX to XII summarize the input data used for this case study. Through applying the proposed methodology, the suggest EOL disposition for a hedge trimmer is graphically described in Figure 4.5.

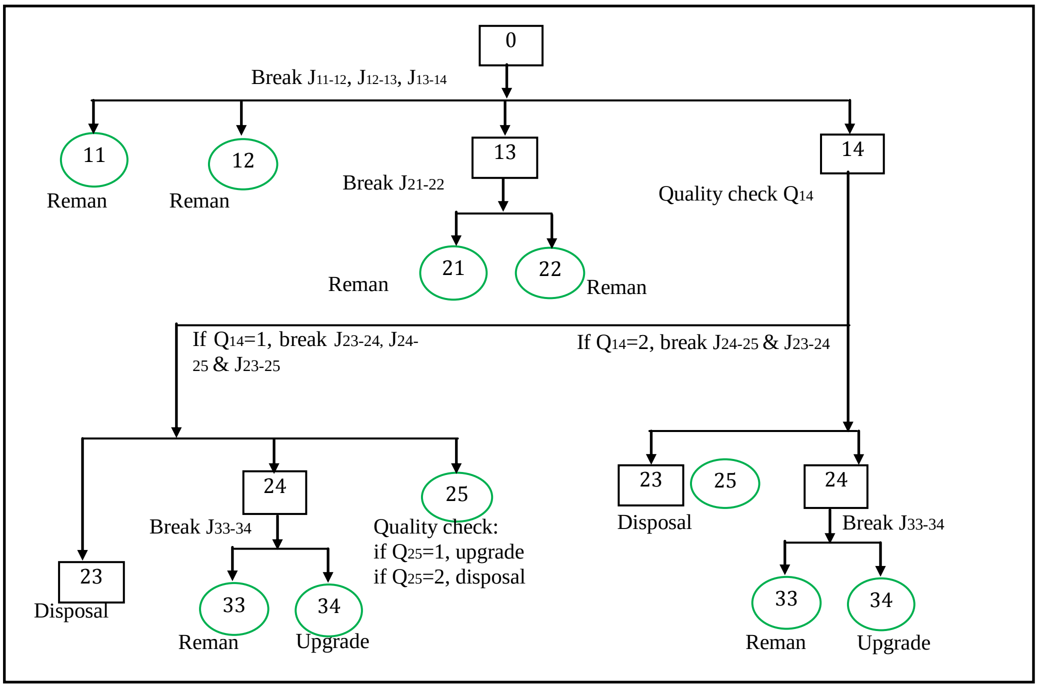


Figure 4.3: EOL strategy planning for an alternator

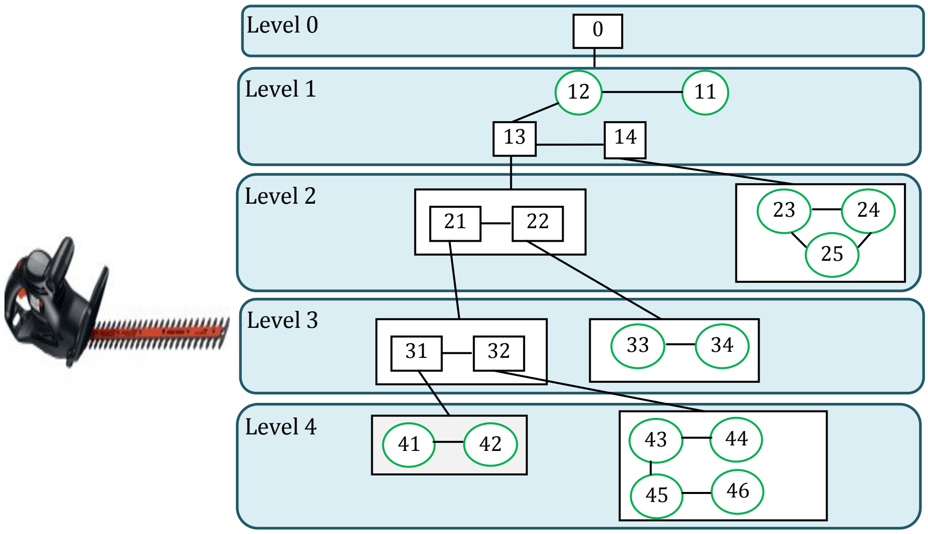


Figure 4.4: HALG representation for a hedge trimmer

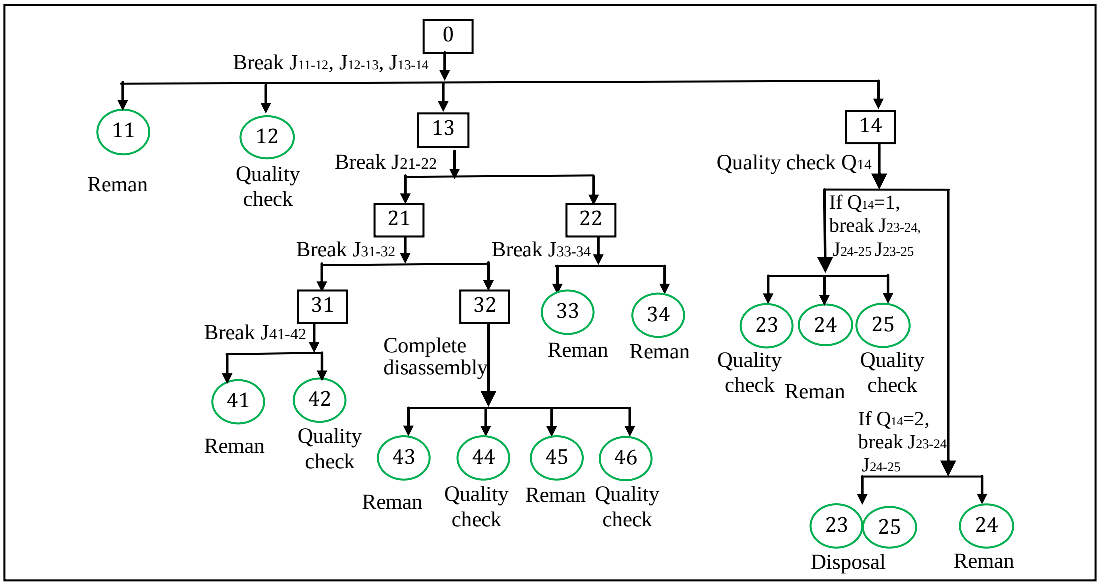


Figure 4.5: EOL strategy planning for a hedge trimmer

4.4 Results and Discussion

The proposed methodology comprises three phases, which involve both qualitative and quantitative analyses to ensure the completeness of operational, technological, economic and environmental decisions. In the first phase, the simplest and quickest inspection is conducted so that many obviously non-usable subassemblies or components are rejected and to ensure only useful items proceed to the next decision making stage. This phase is meant to establish if it is possible and/or necessary to remanufacture a given core or component, from operational and technological perspectives. For example, washers, screws, springs, etc., of the alternator and the hedge trimmer are identified in this phase as “non-usable” components, and therefore are excluded from further examination. In the second phase, a quantitative analysis from the economic and environmental aspects is conducted through dynamic programming in a bottom-up manner. The results from this analysis are the quality-dependent EOL strategy as well as the suggested disassembly depth as shown in Figure 4.3 and Figure 4.5, which constitute the basis and knowledge to assist the actual remanufacturing decisions. The final EOL decision can only be made during the actual disassembly process, where the quality of the subassembly is inspected and sufficient information has been gathered. In the third step, quality inspection is performed at points which would lead to different EOL decisions being made, e.g., quality check is required for 14 and 25 of the alternator. It should be noted that during the reconditioning process, "remanufacturable components" will be continuously inspected until they have been determined to be accepted or have failed, to ensure the quality of the remanufactured product for the next life cycle, which, however, is not the focus of this study.

The results of the two case studies have showcased the applicability of the proposed methodology on determining the disassembly and recovery strategy that should be carried out in order to handle a flow of returned products. As mentioned previously, the quality of the returned product would influence the recovery strategy. Due to the lack of information before disassembly, the quality state of the components released by a disassembly step usually involves uncertainty. To deal with this uncertainty and maximize the economic and environmental rewards of every disassembly step, a quality classification scheme, transition probability and expected value calculations are employed. The results are a complete set of conditional assignment rules as shown in Figures 4.3 and 4.5. For example, if subassembly 14 of the hedge trimmer is in "good condition" (q=1), a complete disassembly strategy will be suggested, otherwise, only component 24 will be extracted from the subassembly, leaving the rest of the components to be disposed as a whole without further disassembly. Note that in this study, the quality of a return flow is reflected using simplified technical states, namely “good condition” (q=1) or “malfunctioning” (q=2). However, the classification could be further defined with more quality grades or the aspect of classification could be expanded to include composition, usage condition, quantity, etc., to account for greater uncertainty or possibilities that might be involved in EOL decision making. Meanwhile, the results of the case studies also demonstrated the importance of considering disassembly cost during EOL strategy planning. For example, in the alternator case, if the regulator (with q=1) is considered independently, remanufacturing might be a viable strategy than disposing and replacing. However, if the disassembly cost between the brush and the regulator is considered, it would be a better strategy to dispose and replace the regulator and the brush together without further disassembly. The insight gained from this result can also be used as design feedback to facilitate product design for remanufacturing, so as to reduce the disassembly cost and make the product more viable for remanufacturing.

In the proposed methodology, the optimization objective is to maximize the economic surplus and minimize the environmental impact. To illustrate the impact of the objectives on the results obtained, two different objectives are investigated in this section. It is observed that when the objective is solely to maximize the economic aspect, some recovery decisions will become quality-dependent, e.g., subassembly 21, 22, 31, 32 of Hedge Trimmer. That is, if the quality of the subassembly is good, disassembly is recommended, otherwise, direct disposal and replacing with new component is recommended. Figures 4.6 and 4.7 illustrate these results. When the objective is to minimize the environmental impact, a complete disassembly strategy is recommended to retain the value of the components regardless of the cost involved. Figures 4.8 and 4.9 illustrate these results. Therefore, the EOL decisions depend on the objective(s) set by the users, e.g., the company management and the proposed methodology has provided an effective and quantitative approach for comparing environmental impact with economic consideration.

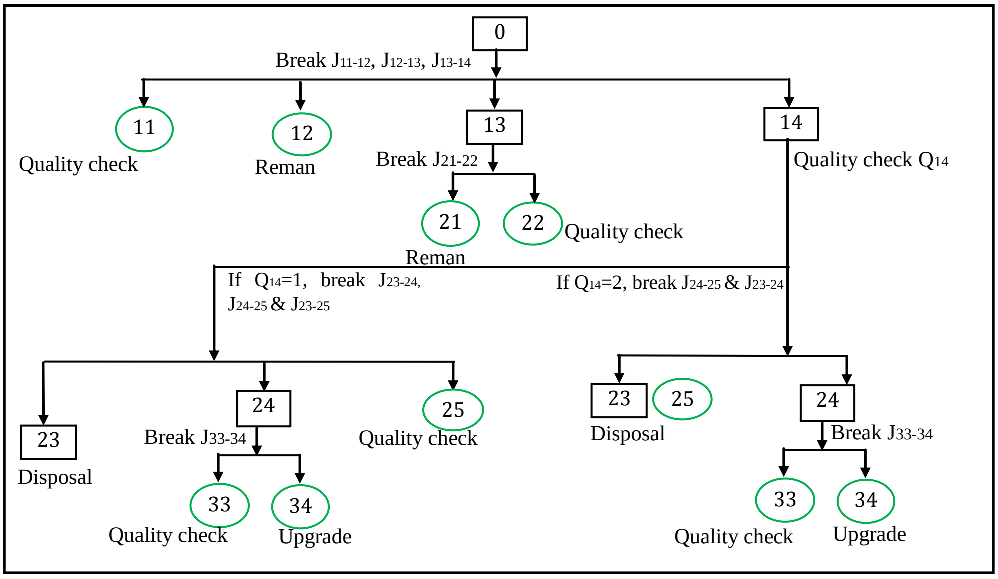


Figure 4.6: Results considering economic impact only (alternator)

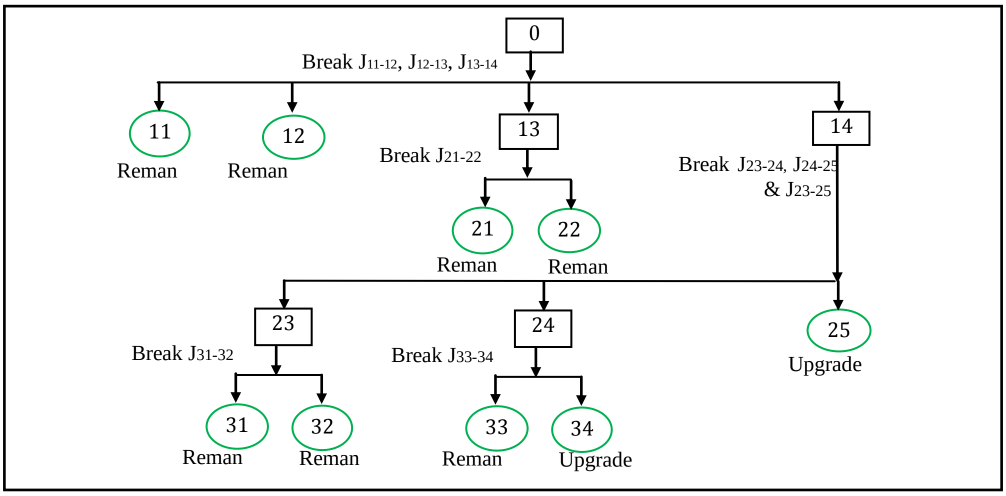


Figure 4.7 : Results considering economic impact only (hedge trimmer)

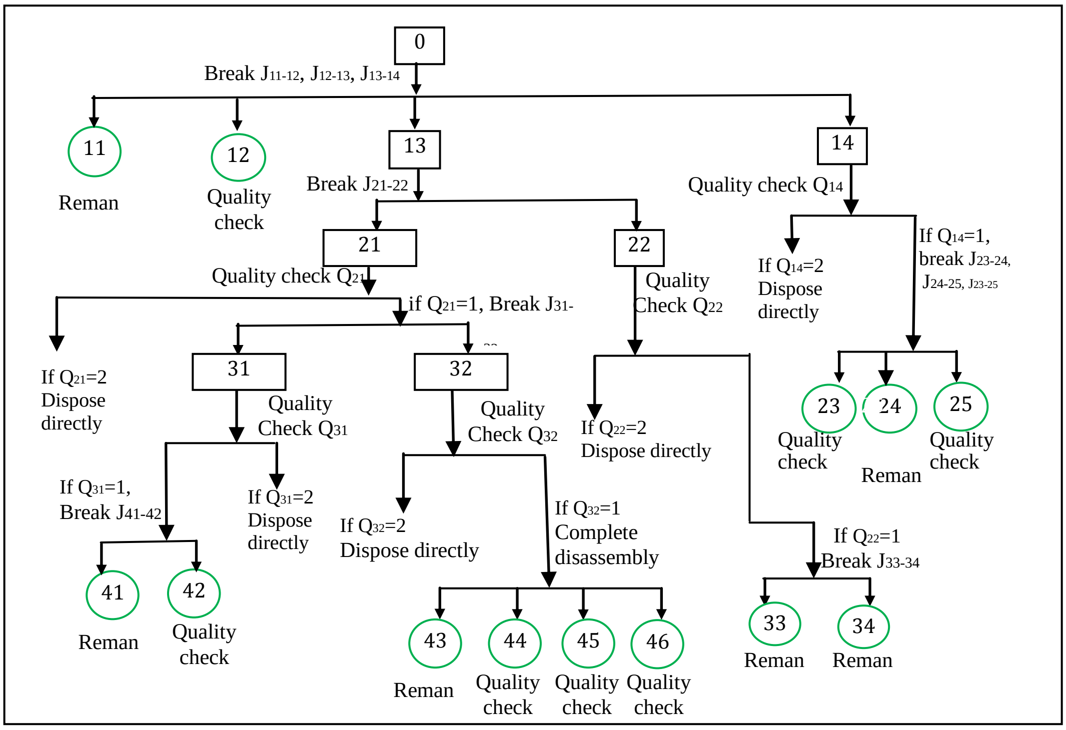


Figure 4.8: Results considering environment impact only (alternator)

A computation tool based on the MS Excel@ platform has been developed to implement the proposed methodology. Hence, instead of relying on *ad hoc* engineering judgement, decision makers can refer to the proposed tool for the optimum EOL decision, that corresponds to maximum economic and environmental rewards; as well as the necessary depth of disassembly to avoid the waste of time and effort on separating the components that could have been disposed together. Meanwhile, the addition of the qualitative analysis, which incorporates the technological and operational considerations, has further ensured the comprehensiveness and reliability of the decision making. These characteristics make the proposed tool potentially applicable for determining the tactical EOL strategies for different types of returned products. Note that the proposed methodology assumes that products are dealt in a decoupled way and the financial synergy resulting from sharing set-up costs among multiple products is not considered. However, if the results of one-product optimization are used on the multiple-product level, it is necessary to iterate the proposed methodology with the readjusted costs and revenues, in order to recalculate the EOL strategy on the single-product level. These issues are subject to further research.

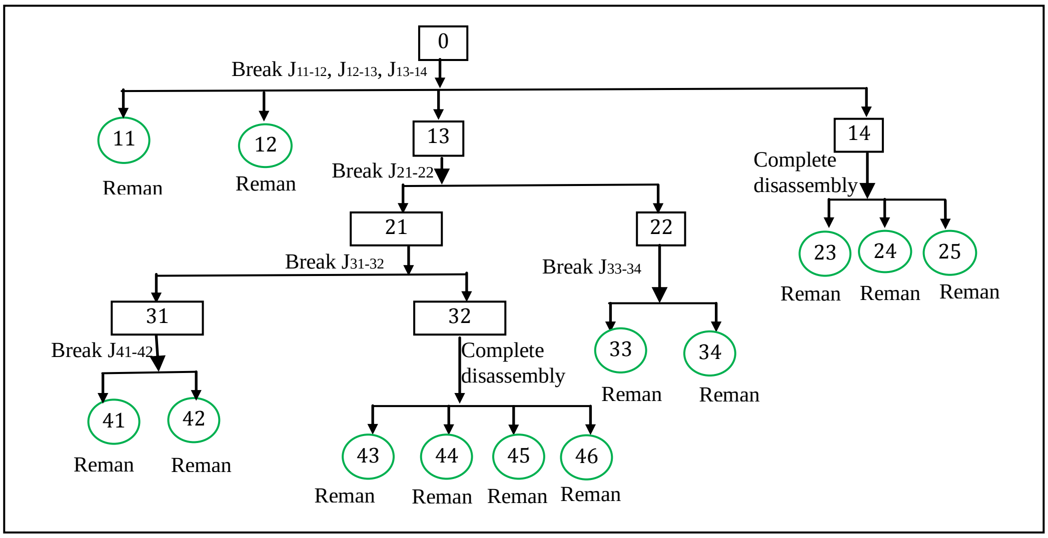


Figure 4.9: Results considering environment impact only (hedge trimmer)

4.5 Summary of the chapter

A methodology is proposed in this chapter to facilitate the EOL decision making for components of returned products. This model makes contributions in (1) considering the quality of the components and returned product by using the concept of conditional probability; (2) using both qualitative and quantitative analysis to ensure the completeness of operational, technological, economic and environmental decisions; (3) adopting HALG to represent the product structure and the interconnections among components, and thus determine the optimal depth of disassembly and the EOL fate for each component. The proposed model is universal in application, and can be adapted for different product types by adjusting the data and variables involved in the model. For further research, disassembly sequencing planning can be integrated with the proposed methodology to further improve the disassembly efficiency and reduce the disassembly cost. The technical status of the components can be defined in more dimensions, e.g., composition, usage condition, quantity, etc., to provide more information for EOL strategy planning. Artificial intelligence techniques, e.g., fuzzy logic, can be applied to address the subjectivity of the decision-making process and improve the reliability of the proposed methodology.

5. DISCUSSION

This chapter will discuss the integration of the DRRA system and illustrate the overall framework with a case study.

The primary objective of this research work is to develop a Design for Remanufacturing and Remanufacturability Assessment (DRRA) tool, to be used at the early product development stage to assess the suitability of a product and its components for remanufacturing and to make suitable modification of the design to improve the potential of product for remanufacturing. The DRRA tool can also be used during the product return/service stage, to assist generating the recovery plan of the returned products taken into account their quality variation. Though the methodologies are discussed individually, they are connected internally by feeding forward and backward of the product knowledge, such as product design features, EOL strategy planning, and remanufacturing considerations. The flows of the product knowledge, along with the proposed decision support tools have formed collectively the proposed DRRA tool as seen in Figure 1.2. The flow of the product knowledge between the proposed methodologies is discussed as in the following and illustrated with an alternator case study.

a) **Feed forward of the product knowledge from the early stage EOL strategy planning to EOL stage recovery plan generation**

Using the EOL strategy planning tool presented in section 3.1, all the necessary factors which affect remanufacturing will be considered and the subassemblies and the parts which are feasible candidates for remanufacturing can be identified successfully. Take an alternator as an example, through the remanufacturability screening test, the components such as stator, rotor, housing, and fan can be easily identified as reusable components for remanufacturing. On the other hand, due to limited remaining useful life and remanufacturing capability, components such as slip rings, springs, washers, screws are classified as non-feasible candidates for remanufacturing and excluded for further remanufacturing analysis. This EOL information, together with the bill of materials, disassembly instruction, repair manual will form the valuable product knowledge and be fed forward to the EOL stage. Remanufacturers, during the product EOL stage, can employ this information to conduct operational and technological assessments to extract the reusable components for remanufacturing, develop the HALG for the alternators and generate a preliminary recovery plan for the returned type of the alternator, as illustrated in sections 4.3 and 4.4. This, to certain extent, can save the effort of remanufacturers to reestablish the product knowledge which already exists.

b) **Feed forward and backward of the product knowledge between early stage EOL strategy planning and early stage design for remanufacturing**

Besides assessing the remanufacturability of the products and components at early design stage, the proposed research will take a proactive measure to improve the potential of the product for remanufacturing, through developing an effective and efficient product design support tool. As this design tool is meant to be applied to the components or parts that have the potential for remanufacturing, it would require pulling EOL related information from product EOL strategy planning tool. Take the alternator as an example, when its reusable components, such as housing, belt fitting, fan and bearing, have been identified using the proposed EOL strategy planning tool, designers can make use of this information to proceed with design for remanufacturing. As illustrated in section 3.2, case study 2, designers can vary the materials selection for the selected components and examine their impact on both remanufacturing efficiency and life cycle performance. On the other hand, whenever there is any design modification employed, the redesign specification can be send back to product EOL strategy planning tool to go through remanufacturability analysis or re-run with the optimization model to examine their impact on EOL recovery strategy. Details of this have can be seen in Section 3.1 discussion part.

c) **Feed backward of the product knowledge from EOL remanufacturing stage to early stage product design for remanufacturing**

During remanufacturing process, remanufacturers will also establish their own product knowledge, which in many case complement and even overcome the available product information. For example, as mentioned in the alternator case study in section 4.3, if the joining between the regulator and brush can be designed to facilitate the disassembly process, it would be more viable to remanufacture the regulator rather than dispose and replace it. This kind of experience about the remanufactured product and operations, along with documentation of core quality, defect measurement, compose the value product knowledge, which can be fed back to early design stage to facilitate product design for remanufacturing. When designers receive this information, they will have a better understanding about the design features that might impede or facilitate the remanufacturing process and addressed the remanufacturing concern through proper product feature design.

The increase in product knowledge, through the feeding forward and backward of the product information, contributes towards a more efficient DRRA system, which consequently would promote transparent and accessible product life-cycle information flow and stimulate the product remanufacturing development.

6. CONCLUSION

In this section, the contribution of the proposed research work will be summarized. A critical review of this research and some suggestions for further research will also be presented.

6.1 Research Contribution

The contribution and novelties of the approach are summarized as follows:

(a) Analyzing remanufacturability of a product and its components at the early product development stage, by addressing the comprehensive aspects of remanufacturing considerations and utilizing NSGA-II to determine explicitly a Pareto set of optimal EOL strategies;

(b) Investigating a large number of scenarios as necessary in EOL strategy planning, such as change of remanufacturing cost, product design, landfill cost, and suggest appropriate strategies to accommodate the change of situational variables or measures to improve product design;

(c) Steering a product design towards higher remanufacturability from four major design aspects, namely material selection, material joining methods, structure design and surface coating;

(d) Examining the impact of remanufacturability enhancement design features on both remanufacturing performance and overall product life cycle performance using Fuzzy TOPSIS analysis and life cycle thinking approach respectively, so as to achieve a robustness and comprehensiveness of the remanufacturing design improvement;

(e) Ensuring the operational, technological, economic and environmental considerations are well addressed and incorporated into product recovery planning process through qualitative and quantitative analyses;

(f) Utilizing the stochastic dynamic programming and probability theory to analyze the impact of the quality of the returned products on EOL decision making;

(g) Adopting HALG to represent the product structure and the interconnections among components and thus enable the determination of the optimal depth of disassembly and the EOL fate for each component.

6.2 Limitation and Recommendation

In this research work, the proposed methodologies have been demonstrated with case studies to show their utility and applicability. However, there is a need for more case studies with different types of the products to further validate and improve the research finding and design tools. Meanwhile, note that the proposed methodologies for remanufacturability assessment assume that products are dealt with in a decoupled way, i.e., without considering the financial synergy resulted from sharing reverse logistic cost or setup cost with other product types within the factory. When a full-scale treatment of economic analysis is carried out, the proposed methodology should be iterated with the readjusted cost value, such as the reverse logistic cost or resale price, in order to recalculate the EOL strategy on the single-product level. In addition, throughout the thesis, energy has been used as the major environmental impact indicator, the reason is that energy consumption has been confirmed by several studies (Sutherland et al., 2008; Huijbregts et al., 2006; Hula et al., 2003) as a major contributor to a number of environmental problems, e.g., global warming, acidification, eutrophication, stratospheric ozone depletion. If other factors of environmental impact are taken into account, like raw material usage, aquatic/terrestrial toxicity, smog formation etc., the result of the product EOL decision making might be different depending on weight assigned for different environmental impact categories.

Meanwhile, there are a few issues that have not been considered in this research, which can be further explored and developed to improve the contributions made in this research:

(a) Integration design for remanufacturing with product service system

The intense worldwide competition among manufacturers has motivated companies to shift the paradigm from a product sale to service business model. The service business model is also referred to as "functional sales/economy", "product service combinations", "product-to-service", "servicing and product service systems (PSS)". The reason for this shift is that companies have discovered the profit which could be gained during the product's use phase as well as the economic opportunities in the aftermarket of the product. An example of service business model is when the companies provide the service of washing clothes instead of selling the actual washing machine. On the customer side, they only need to pay for the number of the laundry loads used, instead of purchasing the washing machine itself (Sundin and Bras, 2005). This paradigm shift has led OEMs to focus more on the product maintenance and remanufacturing (Sundin and Lindahl, 2008) and provide them with more incentive to improve the potential of the product for remanufacturing through design, so as to extend the physical life cycle of their products and make profit from the product service system. This paradigm shift has also called for insight and research work into product design requirement that would facilitate both service selling and remanufacturing and how this combination will work in practice (Hatcher et al., 2011).

(b) Design for remanufacturing with embedded sensor

Uncertainty in the quality and quantity of product return has been identified as one of the major issues that complicate the remanufacturing strategy planning process. To address these issues, using embedded smart sensors has been proposed to monitor the useful information, such as product identity, constituent components, remaining service life, remanufacturing history of a product and thus facilitate EOL decision making (Fang et al., 2013). One of the examples of is to use Radio-Frequency Identification (RFID) to retrieve, update and manage product information throughout entire life-cycle (Kiritsis et al., 2003; Parlikad and McFarlane, 2007). Despite the benefit of using embedded smart sensors for remanufacturing, there are still challenges and issues that limit the application of sensors, which shall be addressed in the product design stage, such as the methods and location to mount the sensors without compromising the product functional performance and reliability, the capability of the sensors to store and transmit the information as well as the economic justification of installing embedded sensors. Further investigation on using embedded smart sensors is imperative, so as to facilitate the remanufacturing operations and decision-making at the EOL stage.

(c) Remanufacturing knowledge database

In order to assist decision makers in the application of the proposed Design for remanufacturing decision support tool and to simplify the computation complexity, a computation tool based on Visual C# has been developed, which allows for fast computation and ease of use of this methodology. The future work can focus on developing an “expert system” to automate the evaluation process so as to enable the user to input minimum rating for several criteria. This capacity can be achieved through remanufacturing expert knowledge, empirical evidence from case studies, or theoretical derivation. Such expert systems would be of significance for users, especially the designers who lack required remanufacturing knowledge and understanding, when evaluating the design candidates with respect to remanufacturability.

LIST OF PUBLICATIONS

a) Journal publications:

1. Yang S.S., Ong S.K., Nee A.Y.C. (2014): EOL strategy planning for components of returned products, International Journal of Advanced Manufacturing Technology, Vol. 77, Iss. 5-8, pp 991-1003.

2. Yang S.S., Nasr N., Ong S.K., Nee A.Y.C. (2015): Designing automotive products for remanufacturing from material selection perspective, Journal of Cleaner Production, under review.

3. Yang S.S., Nasr N., Ong S.K., Nee A.Y.C. (2015): A holistic decision support tool for remanufacturing: end-of-life (EOL) strategy planning, International Journal of Production Research, under review.

b) Conference publications:

1. Yang S.S., Ong S.K., Nee A.Y.C. (2013): Design for Remanufacturing - a Fuzzy-QFD Approach, in Proceedings of 20th CIRP International Conference on Life Cycle Engineering, Singapore, 17-19th April, pp. 633-638.

2. Yang S.S., Ong S.K., Nee A.Y.C. (2014): Towards implementation of DfRem into the product development process, in Proceedings of 12th Global Conference on Sustainable Manufacturing. Johor Bahru, Malaysia, 22–24th September, pp. 565-570.

3. Yang S.S., Ngiam H.Y., Ong S.K., Nee A.Y.C. (2014): The Impact of Automotive Product Remanufacturing on Environmental Performance, in Proceedings of

22th CIRP International Conference on Life Cycle Engineering, Sydney, Australia, 7-9 April, pp. 774–779.

4. Yang S.S., Ong S.K., Nee A.Y.C. (2015): A Decision Support Tool for Product Design for Remanufacturing, 13th Global Conference on Sustainable Manufacturing, Ho Chi Minh City/ Binh Duong, Vietnam, 16-18th September, accepted.

c) Book chapter publications

1. Yang S.S., Ong S.K., Nee A.Y.C. (2013): Product Design for Remanufacturing, for Handbook of Manufacturing Engineering and Technology, Springer, Part XI, Vol.6, Chapter 87, p.3195-3217, ISBN 978-1-4471-4669-8.

d) Presentation

1. Yang S.S., Nasr N., Ong S.K., Nee A.Y.C. (2014): Designing automotive products for remanufacturing from material selection perspective, 3rd Annual World Remanufacturing Summit, Rochester, NY, USA, Sep 2014.

2. Yang S.S., Nasr N., Ong S.K., Nee A.Y.C. (2014): A holistic decision support tool for remanufacturing: end-of-life (EOL) strategy planning, 3rd Annual World Remanufacturing Summit, Rochester, NY, USA, Sep 2014.

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APPENDIXES

Appendix I: Product design guidelines for remanufacturing

Table A.1: Product design guidelines for remanufacturing

Remanufacturing process	Remanufacturing requirement	Design criteria
Reverse logistics	• Basic description of the product • Avoid damages during transportation	• Labels, graphical communication, packaging or even the form of a product could be positioned on the packaging. • Sufficient clearance and support at the base • Avoid structures extruding outside
Disassembly	• Easy access to internal regions • Easy to loosen joints/fasteners • Reduce the variation of the tools used • Prevent part damage during the disassembly process • Prevent the corrosion of parts • Clear instruction of the products disassembly process • Easy access to the fastener/joints • Easy identification of the fastener • Using one disassembly direction • Multi-disassembly should be possible with one operation	• Time to remove items for access • Number of items to remove for access • Number of fastener to remove • Number of different tools to unlock the joints • Number of permanent joints • Number of parts damaged • Number of fasteners damaged • Isolate the part from the elements • Use non-corrosive materials • Disassembly layout /instructions provided • Position of the parts • Type of fasteners/joints • Types of parts • Position of the fasteners/joints; • Standardization of the fasteners/joints
Sorting and inspection	• Ease of classification of the components • Ease of assessing the condition of the	• Parts are identical or grossly dissimilar • Standardization of the parts • Small number of components and connections

	components • Request for more objective testing methods • Tools to facilitate the sorting process • Ease in detecting wear and corrosion • Component information are clearly indicated (life cycle, composition, wear indicator etc.) • Testing points are easy to access	• Color coding/ numbering system for similar parts • Small number of inspection tools • Simple part test • Description of life cycle, composition, wear indicator are provided
Cleaning	• Accessibility of the internal parts • Simple method for cleaning • Simple inner and outside surfaces • Standard cleaning methods • Less wastes and health concerns • Less variation of the cleaning methods • Instruction for cleaning methods • Labels and instruction to withstand cleaning processes	• Number of cavities/corners difficult to clean • Surface roughness • Total waste generated • Time to clean • Total cleaning material used • Specify cleaning methods • Labels and instruction are able to withstand the cleaning process • Type of materials; • Shape of the parts
Reconditioning	• Parts are robust • Avoid subjective criteria • Fewer parts for replacements • Avoid technological or aesthetical obsolescence • Modularity updatable • Clear information of the product displayed • Texture areas are refurbishable	• Bulky – over design • Wear resistant surface design • Number of the usage cycles • Number of wear and failure prone positions • Number/cost of reparable components • Technological cycle of core components • Aesthetical cycle of core components • Component modularity • Upgradability of components • Contains a tracking method for life • Number of discarded components • Number of parts refurbished • Number of parts replaced

Reassembly and testing	• Ease for adjustments • Capable and adaptable for upgradability • Simple methods for testing	• Number of adjustments • Time to reassemble • Time of final testing • Upgraded configurations assembly without modification

Appendix II. Mathematical models, software tools or statics reference for design for remanufacturing

Table A.2: Mathematical models, software tools or statics reference for design for remanufacturing (partially cited from Hatcher et al., 2011)

Approach	Author(s)	Format	Style	Key purpose	Design stage	Advantages	Disadvantages	Use in Industry
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)	Calculations/software	quant	Assess remanufacturability	Detail	• Process oriented • Familiar concept (DfMA)	• Complex • Retrospective • No guidance • Complex	No
DfRem tools	Yang et al. (2015)	Calculations/software	quant	Selection of most feasible design	Detail	• Lifecycle thinking	• Complex •	No
RemPro matrix	Sundin (2004)	Reference	qual	Guidance, prioritization of issues	Concept develop	• Simple • Offers guidance process	• Subjective • No guidance	No
REPRO2	Zwolinski et al(2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)	software	qual	Decision making, provide past examples	Concept generation	• Early in design process • Does not require extensive knowledge • Offer guidance	• Subjective	No
DfRem guidelines	Ijomah (2009); Ijomah et al (2007a); Ijoman (2009)	Reference	qual	Guidance	Concept generation	• Simple • Offers guidance	• Subjective • Lack lifecycle thinking	Unknown
DfRem Metric	Du et at. (2012)	Calculations/software	quant	Assess Remanufacturability Suggest	Detail/redesign	• Offer guidance	• Complex • Retrospective	No

				improvement				
Hierarchical decision model	Lee et al.(2010)	Calculations	quant	Design of product architecture for most profitable disassembly	Embodiment	• Lifecycle thinking	• Not holistic	No
Energy comparison tool (CED)	Yang et al. (2014b)	Calculations	quant	Compare product overall life cycle	Detail	• Lifecycle thinking	• No guidance	No
Component reliability assessment	Zhang et al. (2010)	calculations	quant	Remanufacturing strategy decision making	Embodiment	• Customer focused • Process oriented	• Not holistic • No guidance	No

Appendix III: Design aids that have been appropriated to facilitate DfRem

Table A.3: Design aids that have been appropriated to facilitate DfRem (partially cited from Hatcher et al., 2011)

Approach	Author(s)	Format	Style	Key Purpose	Design Stage	Advantage	Disadvantage	Use in Industry
Modularization	Wang et al. (2013)	Concept	Qual	Traditional: improve manufacturing efficiency Reman: ease of disassembly	Concept develops	• Familiar concept	• Not holistic • No guidance	Yes
FMEA	Abdullah et al. (2013)	Paper/ software	Quant	Traditional: prioritize and prevent product failure Reman: reduce waster	Concept develops Redesign	• Familiar concept • Lifecycle thinking • Process oriented	• Not holistic • Reliant on reman-OEM feedback • No guidance	Yes
Platform design	King and Burgess (2005)	Concept	Quant	Traditional: reduce manufacturing costs and retain customer choice Reman: simplify process organization	Concept develops	• Familiar concept • Lifecycle thinking	• Not holistic • No guidance	Yes
Disassembly	Chiodo and Ijomah (2009)	Concept	Qual	Efficient disassembly	Concept develops	• Process oriented	• Not holistic	No
Design for Environment tools	Pigosso et al. (2009)	various	Varies	Improve environmental performance	Various	• Lifecycle thinking	• Not holistic • complex	No
Fuzzy-QFD	Yang et al. (2013)	Paper/ software	Quant/ qual	Consider the voice of the remanufacturer, environment concern, economic consideration during early design stage	Concept develops	• Familiar concept • Process oriented	• Reliant on reman-OEM feedback	Yes

Appendix IV: Screenshots of DfRem tool

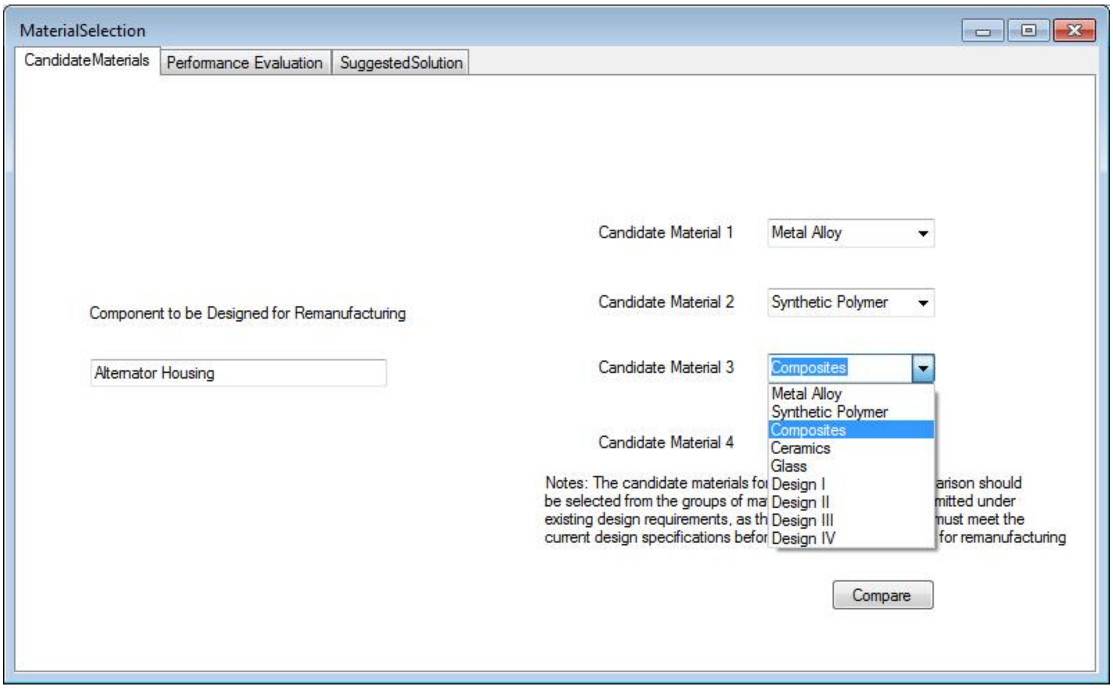

Figure A.1: Define the component and material

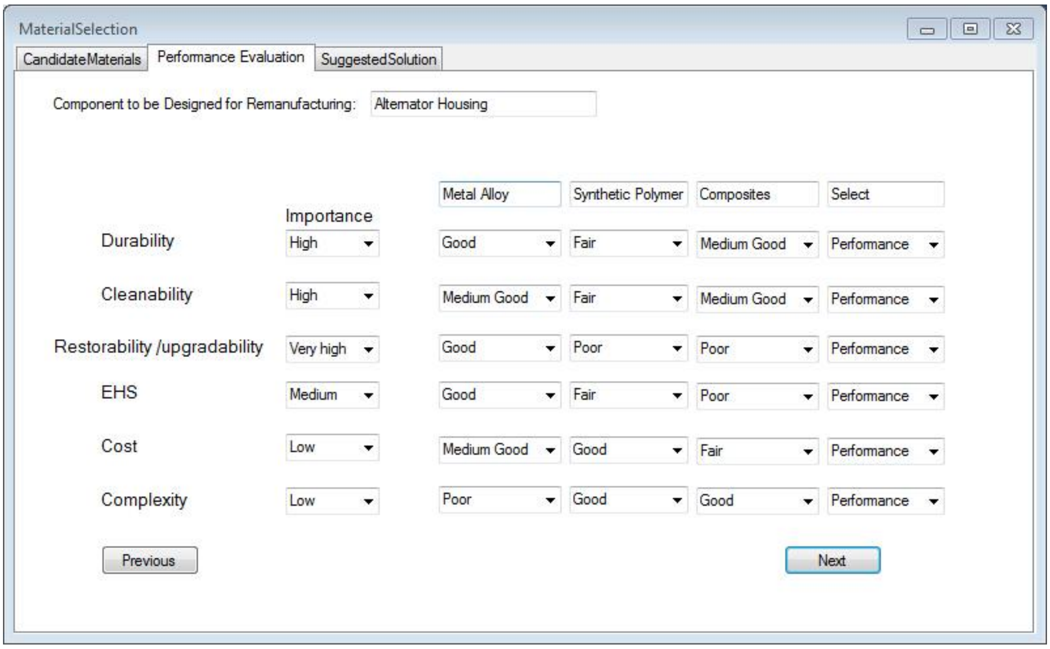

Figure A.2: Evaluate the material performance

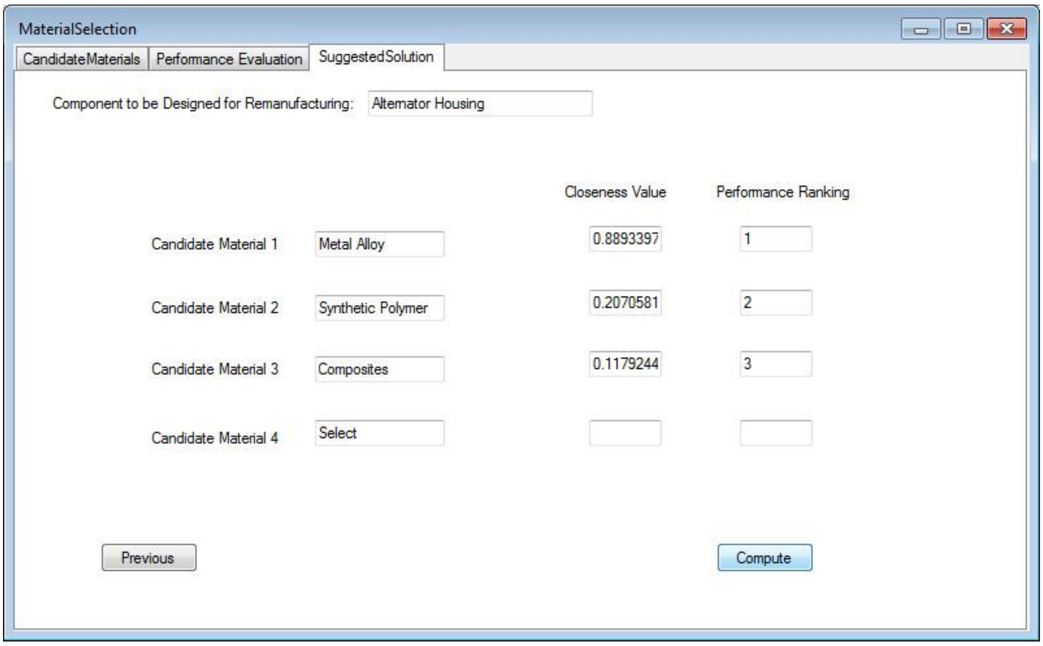

Figure A.3: Calculate the ranking of materials

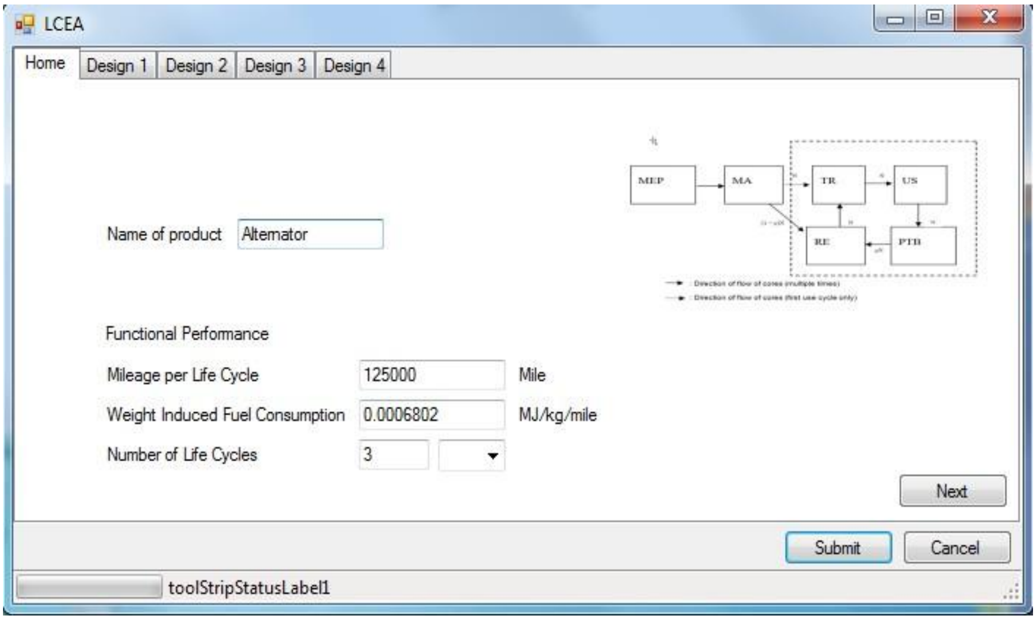

Figure A.4: Define the component and its functional performance

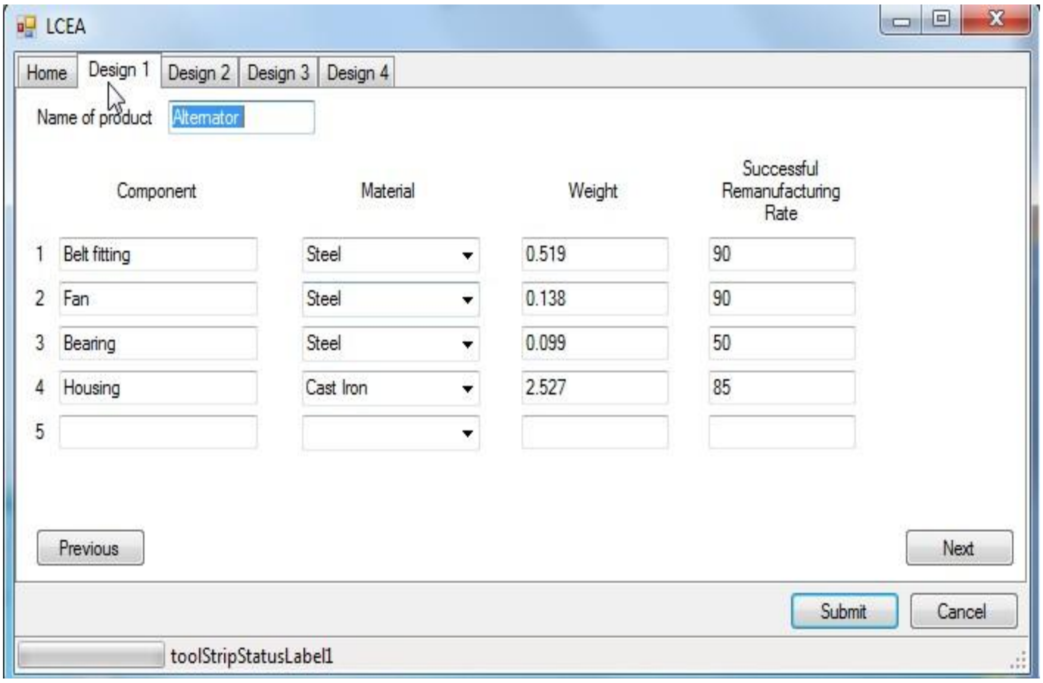

Figure A.5: Define the design specification and evaluate its performance

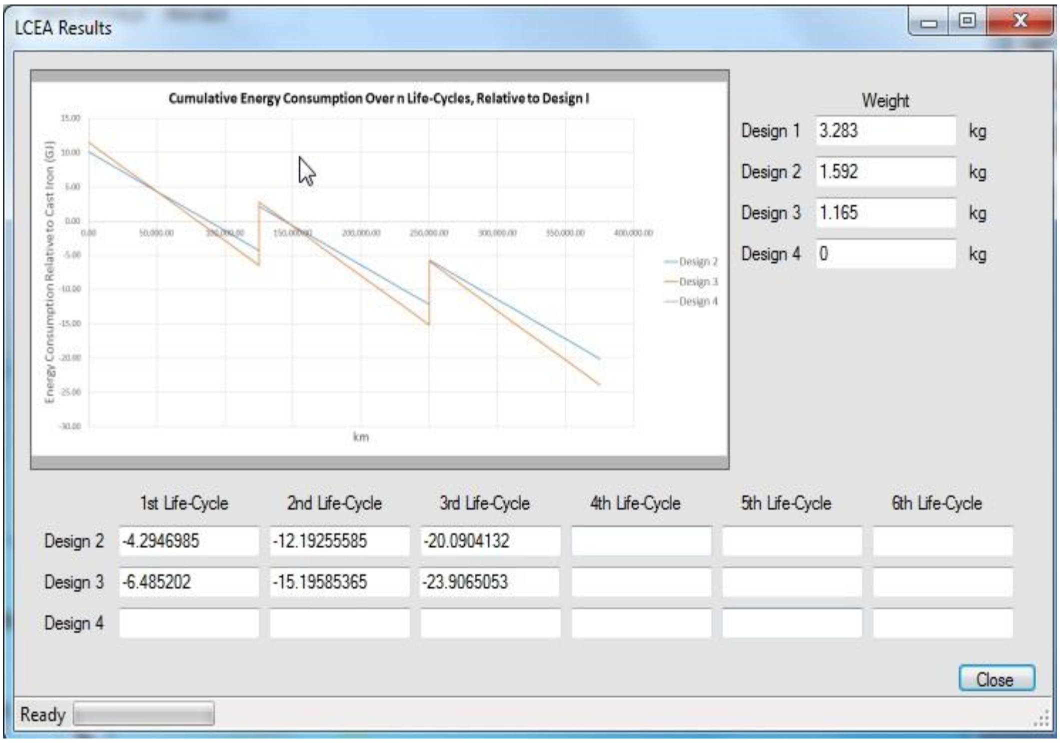

Figure A.6: Calculate the environmental performance of candidate design

Appendix V: Economic index for different EOL options (Alternator)

Table A.4: Economic index for different EOL options (Alternator)

	q=1			q=2		
Part	Upgrade	Reman	Disposal	Upgrade	Reman	Disposal
21	-	-12.00	-35.00	-	-24.00	-35.00
22	-	-3.50	-6.00	-	-7.00	-6.00
31	-	-6.00	-2.00	-	-∞	-2.00
32	-	-4.80	-5.00	-	-∞	-5.00
25	-6.00	-	-8.00	-∞	-	-8.00
33	-	-5.50	-10.00	-	-11.00	-10.00
34	-8.00	-	-20.00	-16.00	-	-20.00
11	-	-4.00	-7.00	-	-8.00	-7.00
12	-	-6.00	-13.00	-	-12.00	-13.00
13	-	-	-41.00	-	-	-41.00
14	-	-	-50.00	-	-	-50.00
23	-	-	-7.00			-7.00
24	-	-	-30.00			-30.00

Appendix VI: Environmental index for different EOL options (Alternator)

Table A.5: Environmental index for different EOL options (Alternator)

	q=1			q=2		
Part	Upgrade	Reman	Disposal	Upgrade	Reman	Disposal
21	-	-0.96	-12.06	-	-1.92	-12.06
22	-	-0.07	-2.42	-	-0.14	-2.42
31	-	-0.03	-0.71	-	-∞	-0.71
32	-	-0.03	-0.20	-	-∞	-0.20
25	-0.09	-	-2.17	-∞	-	-2.17
33	-	-0.16	-4.13	-	-0.32	-4.13
34	-0.96	-	-12.01	-1.93	-	-12.01
11	-	-0.11	-0.63	-	-0.22	-0.63
12	-	-0.27	-6.40	-	-0.54	-6.40
13	-	-	-12.48	-	-	-12.48
14	-	-	-20.22	-	-	-20.22
23			-0.91			-0.91
24			-16.14			-16.14

Appendix VII: Conditional probability of quality level for subassemblies and components (Alternator)

Table A.6: Conditional probability of quality level for subassemblies and components (Alternator)

L	Subassembly	Comp	Pr(1|1)	Pr(2|1)	Pr(1|2)	Pr(2|2)
1	0	11	0.8	0.2	0.4	0.6
		12	1	0	0.5	0.5
		13	0.5	0.5	0.2	0.8
		14	0.5	0.5	0.2	0.8
2	13	21	0.5	0.5	0.2	0.8
		22	0.5	0.5	0.2	0.8
	14	23	0.5	0.5	0.2	0.8
		24	0.8	0.2	0.5	0.5
		25	0.5	0.5	0.2	0.8
3	23	31	0.5	0.5	0.2	0.8
		32	0.5	0.5	0.2	0.8
	24	33	1	0	0.5	0.5
		34	1	0	0.4	0.6

Appendix VIII: Disassembly cost for different disassembly strategies (Alternator)

Table A.7: Disassembly cost for different disassembly strategies (Alternator)

L	Sub-assembl	Break Joint	Independent components	Connected components	Cost
1	0	J11-12	[11]	[12,13,14]	0.4
		J13-14	[14]	[11,12,13]	1.8
		J12-13	[∅]	[11,12,13,14]	2.0
		J11-12, J12-13	[11][12]	[13,14]	2.4
		J12-13, J13-14	[13][14]	[11,12]	3.8
		J11-12,J12-13, J13-14	[11][12][13][14	[∅]	4.2
		∅	[∅]	[11,12,13,14]	0.0
2	13	J21-22	[21][22]	[∅]	0.8
		∅	[∅]	[21,22]	0.0
	14	J23-25	[∅]	[23,24,25]	1.0
		J23-24	[∅]	[23,24,25]	1.0
		J24-25	[∅]	[23,24,25]	1.0
		J23-25, J23-24	[23]	[24,25]	2.0
		J24-25, J23-24	[24]	[23,25]	2.0
		J23-25, J24-25	[25]	[23,24]	2.0
		J23-25,J23-24,J24-25	[23][24][25]	[∅]	3.0
		∅	[∅]	[23,24,25]	0.0
3	23	J31-32	[31][32]	[∅]	1.0
		∅	[∅]	[31,32]	0.0
	24	J33-34	[33][34]	[∅]	1.0
		∅	[∅]	[33,34]	0.0

Appendix IX: Economic index for different EOL options (Hedge Trimmer)

Table A.8: Economic index for different EOL options (Hedge Trimmer)

		q=1			q=2	
Part	Upgrad	Reman	Disposal	Upgrade	Reman	Disposal
11		-0.81	-2.68		-2.44	-2.68
12		-0.41	-1.12		-∞	-1.12
33		-2.53	-8.30		-7.58	-8.30
34		-0.90	-3.00		-2.70	-3.00
23		-0.06	-0.20		-∞	-0.20
24		-0.81	-2.68		-2.44	-2.68
25		-0.18	-0.60		-∞	-0.60
41		-0.74	-2.44		-2.23	-2.44
42		-0.70	-2.29		-∞	-2.29
43		-1.59	-5.27		-4.77	-5.27
44		-0.24	-0.49		-∞	-0.49
45		-2.25	-6.26		-6.76	-6.26
46		-0.74	-2.41		-∞	-2.41
13		-∞	-30.45		-∞	-30.45
14		-∞	-3.47		-∞	-3.47
21		-∞	-19.16		-∞	-19.16
22		-∞	-11.29		-∞	-11.29
31		-∞	-4.73		-∞	-4.73
32		-∞	-14.43		-∞	-14.43

Appendix X: Environmental index for different EOL options (Hedge Trimmer)

Table A.9: Environmental index for different EOL options (Hedge Trimmer)

	q=1			q=2		
Part	Upgrade	Reman	Disposal	Upgrade	Reman	Dispos
11		-0.12	-3.67		-0.36	-3.67
12		-0.02	-0.75		-∞	-0.75
33		-0.23	-1.34		-0.69	-1.34
34		-0.01	-0.05		-0.03	-0.05
23		-0.01	-0.18		-∞	-0.18
24		-0.12	-3.67		-0.36	-3.67
25		-0.02	-0.52		-∞	-0.52
41		-0.07	-1.16		-0.20	-1.16
42		-0.07	-1.19		-∞	-1.19
43		-0.08	-1.37		-0.24	-1.37
44		-0.03	-1.18		-∞	-1.18
45		-0.08	-3.53		-0.24	-3.53
46		-0.10	-0.57		-0.30	-0.57
13		-∞	-10.40		-∞	-10.40
14		-∞	-4.37		-∞	-4.37
21		-∞	-9.01		-∞	-9.01
22		-∞	-1.39		-∞	-1.39
31		-∞	-2.35		-∞	-2.35
32		-∞	-6.66		-∞	-6.66

Appendix XI: Conditional probability of quality level for subassemblies and components (Hedge Trimmer)

Table A.10: Conditional probability of quality level for subassemblies and components (Hedge Trimmer)

L	Subassembly	Comp	Pr(1|1)	Pr(2|1)	Pr(1|2)	Pr(2|2)
1	0	11	0.8	0.2	0.2	0.8
		12	0.8	0.2	0.2	0.8
		13	0.8	0.2	0.2	0.8
		14	0.8	0.2	0.2	0.8
2	13	21	0.8	0.2	0.2	0.8
		22	0.8	0.2	0.2	0.8
	14	23	0.8	0.2	0.2	0.8
		24	0.8	0.2	0.2	0.8
		25	0.8	0.2	0.2	0.8
3	21	31	0.8	0.2	0.2	0.8
		32	0.8	0.2	0.2	0.8
	22	33	0.8	0.2	0.2	0.8
		34	0.8	0.2	0.2	0.8
4	31	41	0.8	0.2	0.2	0.8
		42	0.8	0.2	0.2	0.8
	32	43	0.8	0.2	0.2	0.8
		44	0.8	0.2	0.2	0.8
		45	0.8	0.2	0.2	0.8
		46	0.8	0.2	0.2	0.8

Appendix XII: Disassembly cost for different disassembly strategies (Hedge trimmer)

Table A.11: Disassembly cost for different disassembly strategies (Hedge trimmer)

L	Sub-assem	Break Joint	Independent components	Connected component	Cost
1	0	J11-12	[11]	[12,13,14]	-2.7
		J11-12, J12-13	[11],[12]	[13,14]	-3.0
		J11-12, J12-13, J13-14	[11][12][13][14]	[∅]	-3.3
		∅	[∅]	[11,12,13,14	0.0
	13	J21-22	[21],[22]	[∅]	-0.6
		∅	[∅]	[21,22]	0.0
	14	J23-24, J23-25	[23]	[24,25]	-0.8
		J23-24, J24-25	[24]	[23,25]	-0.8
		J23-25, J24-25	[25]	[23,24]	-0.8
		J23-24,J24-25,J23-25	[23],[24],[25]	[∅]	-1.2
		∅	[∅]	[23,24,25]	0.0
	21	J31-32	[31],[32]	[∅]	-1.5
		∅	[∅]	[31,32]	0.0
	22	J33-34	[33],[34]	[∅]	-2.5
		∅	[∅]	[33,34]	0.0
	31	J41-42	[41],[42]	[∅]	-0.9
		∅	[∅]	[41,42]	0.0
	32	J43-44	[44]	[43,45,46]	-1.5
		J45-46	[46]	[44,43,45]	-1.2
		J43-44, J44-45	[44],[43]	[45,46]	-2.1
		J45-46,J43-45	[45],[46]	[43,44]	-1.8
		J43-44,J45-46	[44],[46]	[43,45]	-2.7
		J43-44,J43-45,J45-46	[43],[44],[45],[46]	[∅]	-3.3