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Nurul Hanna Ismail

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THÈSE

Pour obtenir le grade de

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PRODUCTION**

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préparée au sein du **Laboratoire G-SCOP**
dans l'**École Doctorale IMEP-2**

2-DFR: Un cadre conceptuel destiné aux concepteurs pour un remanufacturing durable

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Résumé

Le remanufacturing est considéré comme une des stratégies clés pour implémenter les principes du développement durable aux produits industriels. Le but du remanufacturing est de récupérer la valeur du produit lorsque celui-ci ne répond plus aux besoins des utilisateurs. Ce processus complexe, qui comporte de nombreuses incertitudes, nécessite d'être pris en compte au tout début de la phase de conception pour que le produit remanufacturé soit adapté aux processus et aux futurs systèmes nécessaire à son remanufacturing.

Un autre aspect essentiel pour aboutir à un remanufacturing durable est de bien planifier et coordonner, sur le long terme, le système global de remanufacturing. La présence de nombreux outils et de méthodes académiques pour faciliter les processus de remanufacturing pourrait permettre de surmonter les défis posés et d'améliorer la qualité et la quantité de produits pouvant être remanufacturés. Malheureusement, ces outils et méthodes sont rarement utilisés par les acteurs de la chaîne du remanufacturing, probablement à cause du manque de plateformes pour en faciliter l'usage.

L'objectif de cette thèse est donc d'aider les concepteurs et les fabricants à:

1. Caractériser les produits et les processus du remanufacturing, en lien avec les principes du développement durable
2. Classifier et aider au choix des outils ou des méthodes pour améliorer la conception (du produit ou des process) dans l'objectif de rendre le remanufacturing durable

Pour atteindre ces objectifs, un cadre à deux dimensions (a Two Dimensional Framework for Remanufacturing - 2DFR), est proposé. Il combine les perspectives liées au développement durable et celles liées au système industriel du remanufacturing. Une liste de caractéristiques (produit ou process) liées au remanufacturing est ainsi proposée dans la première partie de la thèse selon ces deux perspectives. Elle a été validée comme un guide de conception pour le remanufacturing lors d'un atelier dans le cadre du projet européen ERN (H2020). Le 2DFR est ensuite utilisé dans la deuxième partie de la thèse pour développer une méthode de classification des outils de conception pour le remanufacturing. Enfin, une méthode pour guider le concepteur dans le choix de ces outils est proposée. Elle est créée à partir de la liste des caractéristiques du remanufacturing apparues dans la première proposition et de la méthode de classification mentionnée précédemment. Un démonstrateur qui fonctionne comme une interface pour les deux méthodes de classification et de choix des outils est développée. Des études de cas permettent d'illustrer son utilisation.

Les caractéristiques pour des produits et processus de remanufacturing durables définies dans la première proposition offrent ainsi aux utilisateurs un guide lors de la conception et de la prise de décisions. La deuxième proposition, quant à elle, encourage l'utilisation par l'industrie des outils et méthodes existants pour concevoir des produits remanufacturés durables.

Abstract

Remanufacturing is believed to be among the key strategies for sustainable development of industrial products. The aim of remanufacturing is to retrieve the product's inherent value when it no longer fulfils the user's needs. However, it is a non-linear process that poses many uncertainties. Therefore, integrating remanufacturing concerns during the early design phase is necessary to adapt products to the future remanufacturing processes and to the future remanufacturing system.

Another crucial aspect in achieving sustainable remanufacturing activity is to plan and coordinate remanufacturing system in a sustainable way. The presence of various academic tools and methods to facilitate remanufacturing activities might overcome the challenges observed and enhance both the quality and quantity. Unfortunately, these tools/methods are rarely used by remanufacturing stakeholders, probably due to the lack of platform for them to facilitate the usage.

The objective of this dissertation is to help the designers and remanufacturers to:

- Characterize remanufactured products and processes in relation to sustainable development,
- Classify and choose remanufacturing tools or methods to improve sustainable remanufacturing.

To achieve these objectives, a Two Dimensional Framework for Remanufacturing (2DFR) is proposed. It combines the sustainable development and remanufacturing system perspectives. A list of remanufacturing constraints from both perspectives is proposed in the first part of this dissertation. It was validated as a design for remanufacturing guideline during a remanufacturing workshop event in the framework of the European project ERN (H2020). The 2DFR is used again in the second part of this dissertation to develop a method to classify remanufacturing tools/methods. A method to guide and facilitate user in choosing remanufacturing tools/methods is proposed using the list of remanufacturing characteristics listed in the first proposition and the previous classification method. A configurator that functions as an interface for both the classification method and the choosing method is developed. Illustrated case studies are presented to validate its usage.

The characteristics of sustainable remanufacturing products and processes defined in the first proposition offer to the users a comprehensive checklist when designing and making decisions. Meanwhile the second proposition encourages the usage by the industry of the existing academics tools/methods related to remanufacturing.

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Abbreviations

The following table describes the abbreviations used in this dissertation:

AD	Active Disassembly
APMG	All Party Parliamentary Manufacturing Group
APRA	Automotive Parts Remanufacturers Association
APSRG	All Party Parliamentary Sustainable Resource Group
BOM	Bill of Material
BSI	British Standards Institute
CAD	Computer-Aided Drafting
CLOEE	Closed Loop Environmental Evaluations
DfD	Design for Disassembly
DfE	Design for Environment
DFRem	Design for Remanufacturing
DfTPR	Design for Product Taken-Back Parts Reuse
DfX	Design for X
DPF	Diesel Particulate Filter
ECM	Environmentally Conscious Manufacturing
EIS	Environmental Impact Simulator
ELDA	End-of-life Design Advisor
ELSEM	EOL Scenario Evaluation Method
ELV	End-of-Life Vehicle
ERN	European Remanufacturing Network
EU	European Union
FMEA	Failure Mode Effect Analysis
GWP	Global Warming Potential
H2020	Horizon 2020
IMDS	International Material Data System
INPG	Institut polytechnique de Grenoble
IP	Intellectual property
IR	Independent Remanufacturer
IPO	Input Output Process
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life cycle Cost analysis
LCI	Life Cycle Inventory
MAR	Metrics for Assessing Remanufacturability
MFA	Material Flow Analysis
MFA	Material Flow Analysis
MGE	Modular Grouping Explorer
NA	Not Applicable
OEM	Original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PLETS	Product Lifecycle Extension Technique/Process Selection
PLM	Product lifecycle management
PSS	Product Service System
PURE	Product upgradeability and Reusability Evaluator
QFD	Quality Function Deployment
QFD	Quality function deployment

RAMBD	Remanufacturability Assessment Metrics Based on Design
RCORP	Reliability and Cost Optimisation for Reman Process
R-DFLP	Remanufacturing Dynamic Facility Layout Problem
RDMF	Remanufacturing Decision-Making Framework
ReCORE	Research for efficient Configurations Of Remanufacturing Enterprises
Reman	Remanufacturing
REPRO2	Profile of Remanufacturable Product
RL	Reverse Logistics
RNDM	Remanufacturing Network Design Modelling
RSC	Reverse Supply Chain
SAP	Systems, Applications, Products in Data Processing
SI	System Information
SLCA	Social Life cycle Assessment
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WEEE	Waste Electrical and Electronic Equipment

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Chapter 1: Introduction

1.1. Environmental issues in manufacturing industry

During the industrial revolution, environmental issues were not addressed when designing and manufacturing products. However, in the last decade or so, environmental issues has become among the main concern in the industry. This is due to the increasing consumption of energy and material resources in Linear Economy (see Figure 1) by industrialized and developing countries which applies “Take, Make, Dispose” industrial process. Linear Economy takes up the natural resources and disposes waste in landfills or incinerators at the end of product’s life. This has resulted in critical resource constraint, climate change, and waste management issues, which led to the urgency to treat these “wastes” elsewhere. Enforced primarily by governmental regulations and customer perspective, there have been more and more companies who reconsider their business and product planning and management for a more environmental friendly condition.

There are many concepts that have been introduced to solve this problem such as Life Cycle Thinking, Design for Environment (DfE), Environmentally Conscious Manufacturing (ECM), Cradle to Cradle, eco-efficiency. In Europe, the European Commission has agreed to adopt the new concept of Circular Economy where the objective is to maintain the value of products, materials, and resources in the economy as long as possible and to minimize waste. This adoption empowers the existing approaches including cradle to cradle, industrial ecology and any other approach to shift from the linear model production.



Figure 1: Linear Economy (source: Henry, 2016)

1.2. Circular economy

A circular economy is “One that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.” (Ellen MacArthur Foundation, 2015”). The technical cycle means the management of stocks of finite materials. Technical materials are recovered and mostly restored in the technical cycle. Meanwhile the biological cycle involves the flows of renewable materials. Renewable nutrients are mostly regenerated in the biological cycle (See figure 2). This is a viable alternative for the previous Linear Economy and rests on three principles:

- a) **Preserve and enhance natural capital**, by controlling finite stocks and balancing renewable resources flows.

This principle starts by dematerialising utility or delivering utility virtually whenever possible and optimal. When resources are needed, they are selected wisely by choosing renewable or efficient technologies and processes. The natural capital is enhanced by encouraging flows of nutrients within the system.

- b) **Optimise resources yields**, by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.

Included in this principle are the concept of Design for Remanufacturing, refurbishing and recycling to keep the technical components and materials circulating in the system and adding value to the economy. Tighter inner loops are applied in this system whenever possible (i.e. repair, rather than recycle). For biological cycle, the circular systems encourage biological nutrients to re-enter the biosphere safely.

c) **Foster system effectiveness**, by revealing and designing out negative externalities.

This principle means reducing damage to systems and areas.

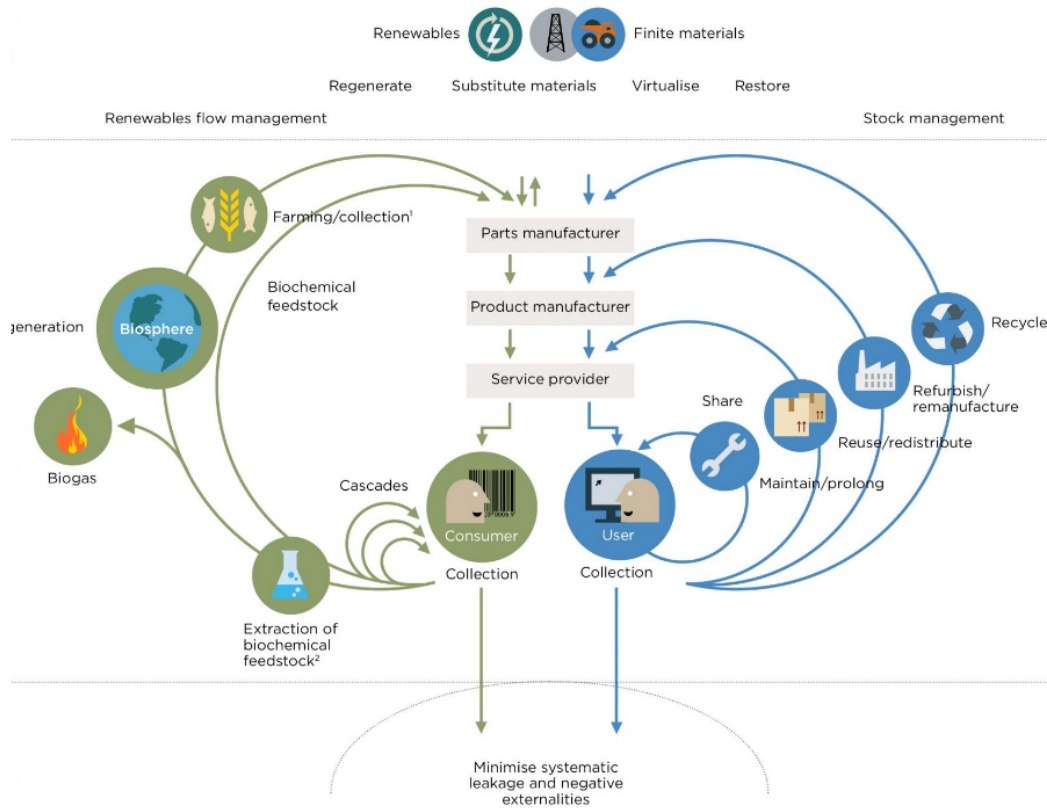


Figure 2: The Circular Economy System Diagram [Source: Ellen MacArthur Foundation,2015]

Circular economy is expected to offer benefits such as reducing the total annual Greenhouse Gas Emission, increasing economic growth and creating jobs, boosting competitiveness and ensuring the security of supply, building economic and environmental resilience, and encouraging innovations. Adopting Circular Economy in Europe starts with applying significant changes in the listed key action areas. In “production” key area, remanufacturing is specifically stated among the key actions as a solution to achieve the key area objectives, which are:

- Provide incentives to boost circular product design
- Create innovative and efficient production processes.

If these objectives are achieved, the final goal for a circular economy that was stated earlier will be potentially achieved too.

1.3. Remanufacturing

Remanufacturing is one of the options used to create a loop in the product life cycle. The British Standards Institution's BS 8887-2 (2009) defines remanufacturing as the process of "returning a product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product."

It is believed that remanufacturing had started as early in the 1940s in the US and the UK during the World War II. At that time, there was an exceptional need to reuse automotive parts due to the scarcity of natural resources which were used to build planes, ships, and tanks for the war. Since then, remanufacturing grows steadily not only in the US and Europe, but also in other parts of the world. With the advancement in technology, the scope of remanufacturing industry has greatly expanded to other various sectors including medical equipment, aerospace, electronics and electrical equipment, and office furniture.

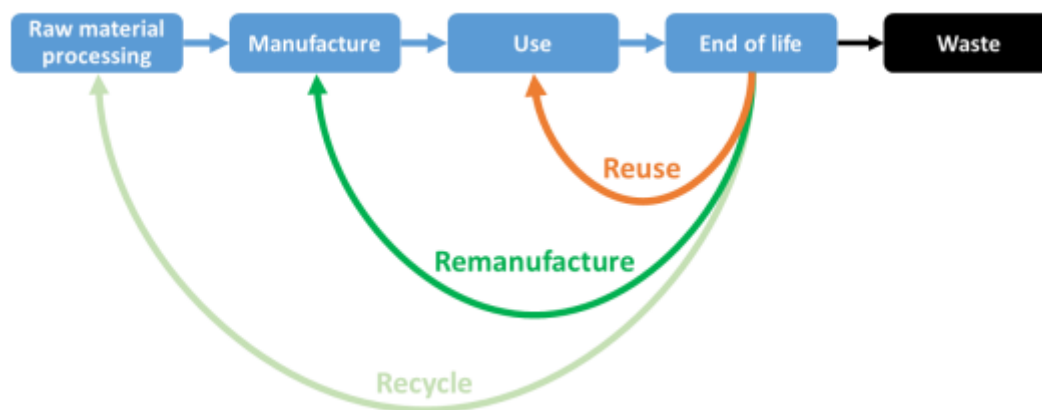


Figure 3: Closed-loop life cycle strategies

According to the strategies described in Figure 3, remanufacturing is the only aspect that ensures the "same as new" quality of products, whereas some materials are downgraded into lower quality materials when they are recycled. Many studies have been done to compare the differences of the existing closed loop strategies regarding the benefits and challenges. APRA Europe has presented the findings from automotive parts that undergone each option in Figure 4 and highlighted the advantages of remanufactured parts compared to others. The finding shows that the strength of remanufacturing process relies on the controlled components (new, rebuild or checked) and the complete process of disassembly and reassembly, which guarantee the quality of outcomes and the fact that they are not owned by other closed-loop options. Giuntini and Gaudette (2003), W Kerr et al.

(2001), Lindahl et al. (2006), Sutherland et al. (2008), Kim et al. (2008), Kara (2009), Baustani et al. (2010), Amaya et al. (2010), Goldey et al. 2010 are among the researchers who have proven the advantages of remanufactured product compared to the new or recycled one, mostly from economic and environmental perspectives.

	used parts	repaired parts	new parts	remanufactured parts
Complete disassembly and reassembly	<input type="checkbox"/>	<input type="checkbox"/>	n. a.	<input checked="" type="checkbox"/>
All Components either new, rebuild or checked	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
High availability	<input type="checkbox"/>	n. a.	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
100% systematic final test	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
No safety risks	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
enviromentally friendly	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>

no
 n. a. not applicable
 partly true
 yes

Figure 4: Comparison of the Closed-loop Options (Source: ("APRA - Automotive Parts Remanufacturers Association - in Europe welcomes you", APRA Europe)

There are many previous studies and published articles dedicated to remanufacturing, which uncover its benefits. From the environmental perspective, remanufacturing activity is normally predicted:

- To conserve energy
- To conserve raw material
- To extend the lives of landfills
- To reduce pollution

Also, from the economic and social point of views, remanufacturing is seen as a business model that could satisfy consumers’ needs (quality product with a lower price), create new job opportunities and new stakeholders, and build company’s good image.

Having listed those advantages, one of today’s most significant challenges in remanufacturing is to ensure that the product has all of those benefits when it is operated. This challenge is significant for remanufacturing due to the complexity (product and remanufacturing process) and uncertainties (timing, quantity and quality of returns,

operation time) in the remanufacturing process. The complexities and uncertainties have made it difficult and doubtful to plan and monitor the process in achieving those benefits. A poorly planned and managed remanufacturing system could hinder the expected remanufacturing benefits as well as causing unnecessary losses.

1.4. ERN: The European Remanufacturing Network

To support the European effort on circular economy and remanufacturing, The European Remanufacturing Network-ERN project was launched in January 2015. It is a two year project, sponsored under Horizon 2020 and has gathered eight partners from six different EU Member States including G-Scop Laboratory (under INP Grenoble). It is the first European Remanufacturing Network with the objective to:

- Encourage new businesses to take up remanufacturing
- Help existing remanufacturers improvise their operations
- Improve competitiveness of remanufacturers domestically and internationally
- Create greater awareness of remanufacturing in the public and policy makers to increase demand and address barriers

The cross-sectorial activities to facilitate knowledge transfer and promote remanufacturing industry have been neglected in Europe over recent years. European remanufacturing could lose its competitiveness to major competitors like the US and China if this need is not fulfilled. Therefore, this project is an important effort to solve the stated problem. This project supports remanufacturers by sharing market studies and best remanufacturing practices in business models, process and design, providing remanufacturing tools, workshops and offering partnerships, and raising the profile of remanufacturers for future European commission policy. Some results of this thesis, related to design for remanufacturing, will benefit this project.

1.5. Design step ensures sustainable remanufacturing

A well-planned remanufacturing activity should start from the early stage of the product design phase. It is important to consider the remanufacture feasibility aspects while designing a product as it can contribute to a significant advantage for the whole remanufacturing process. This importance has led to the introduction of Design for Remanufacturing (DfRem) term as well as the intensive amount of studies on design and its relation to a successful remanufacturing process. However, the definition of “successful

remanufacturing” changes from time to time, which also affects remanufacturing feasibilities. This definition is influenced by the decision factors that a process has to consider. In general, the early design for remanufacturing activities tend to focus more on the economic and technical aspects. Then, the environmental aspect has to be added into the repertoire as another important aspect, followed by the social aspect to follow the concept of sustainable development introduced into the remanufacturing activities. Therefore, it is crucial for this study to help designers to plan and manage remanufacturing activities.

When discussing the importance of helping designers, there is also the need to discuss the design tools, including methods and approaches. In the remanufacturing sector there are many tools, methods, and approaches that were developed to help designers and remanufacturers to decide and plan their remanufacturing activity. Those propositions help the stakeholders who are engaged in remanufacturing activity, including understanding the remanufacturing concept, and guide them in remanufacturing planning and process, to assess remanufacturing activity, and to make decision based on the best practice. However, the large quantity of tools/methods used for remanufacturing might cause another problem related to the choice of tools/methods. Indeed, finding the best tool or method for company’s specific needs related to sustainable remanufacturing is not obvious. We will see that it is better from now to help designers not by introducing a new tool/method but with the implementation of an aid to choose the most appropriate tool/method from the existing design for remanufacturing tools/methods.

1.6. Organisation of the thesis

For the structure of this dissertation, there are five chapters with three main parts. PART I (chapter 2) consists in the review of the current studies in related literature and of established research methodologies. The research questions are then highlighted. In this chapter 2, the remanufacturing concept is discussed in detail, including theories, process, best practices, barriers, and benefits. Besides that, there are also reviews on the remanufacturing and sustainable development perspective, remanufacturing design, and also remanufacturing tools and methods. The problems of choosing and selecting a proper tool/method are raised in the discussions related to the remanufacturing tools and methods.

Through the combination of these insights from the identified literature, Chapter 2 emphasizes on the gaps and research questions that are explained accordingly.

In PART II (Chapter 3 and 4), the results of this study are presented in the effort to solve the problems mentioned earlier. In both chapters, the methodological issues are provided through both theoretical and procedural descriptions, which were used to collect, present, and analyse this study's data. Chapter 3 presents the first proposition regarding the working framework and gives the definition and characterization of remanufactured product that contains the elements for sustainable development. Chapter 4 presents the second proposition related to "how to enhance the usage of remanufacturing tools and methods". A method to classify and choose remanufacturing tools/methods is proposed. A configurator that functions as an interface for both a classification method and a choosing method is developed. Illustrated case studies are proposed to validate its usage.

PART III (Chapter 5) contains discussions, recommendations, and conclusions for the current study, including the reflective evaluation and further research agendas.

Chapter 2: Literature review

2.1. Concept and Definition

Remanufacturing is one of the strategies that are used to close the classic-industrial-linear loop. Besides remanufacturing, reuse, repair, and recycle are among the other strategies shown in Figure 3. According to Guide (2000), remanufacturing represents a higher form of reuse by focusing on the product's value-added restoration. This is different from recycling, which focuses on material recovery (product's value-added is destroyed) and more complex than repair or reuse. In the past years, many researchers have defined remanufacturing on their own term, but most of the definitions were quite close. The following Table 1 are some of the definitions:

Remanufacturing definitions	Source
Remanufacturing is the process of returning a used aircraft parts product to at least original-equipment-manufacturer performance specification and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent	The Remanufacturing Institute (Statham, 2006)
Remanufacturing is an industrial process whereby products referred as cores are restored to useful life. During this process, the core pass through a number of remanufacturing steps, e.g. inspection, disassembly, cleaning, part replacement/refurbishment, reassembly, and testing to ensure it meets the desired product standards"	(Sundin thesis, 2004)
A process that brings a used product back to a new state through reuse, refurbishment, and replacement of its components"	(Amezquita et al.,1995)
Remanufacturing, a process of returning a used product to at least the original equipment manufacturer (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent.	(Ijomah, 2002)

Table 1: Remanufacturing definitions

The following elements are mentioned in each definition:

- Reusing the used product by highlighting the closed-loop concept,
- Having a like-new state/condition which is an advantage that makes it different from other processes,
- Giving quality assurance.

It is important to understand the definition of remanufacturing in order to discard and distinguish some other concepts related to closed-loop strategies, especially when it comes to the real operation. Remanufacturing has always been confused with other very-

similar concepts like reconditioning, repair, refurbish, rebuild, et cetera. A clear definition of each concept could avoid any misconceptions or misinterpretations especially by the customer. Ijomah (2002 and 2007a) emphasized four key factors that differentiate remanufacturing from repair or recondition, which are:

- Warranty: Remanufactured products have an equal-to-new product warranty which is not the case for other concept.
- Greater work: Remanufacturing normally consists of greater work which contributes to a superior quality end-product.
- Lose identity: Remanufactured product will lose their identity since every component has been assessed and an impossible-to-retrieve component will be replaced. This condition is not presented in repair and reconditioning
- Possibility to be upgraded: For certain product and technology, it is possible for an upgrade to occur in remanufacturing. However, this condition is not presented in repair and reconditioning.

Figure 5 presents the other possible processes that come after a product arrives at its end-of-life. In each process, the product's quality level is stated to differentiate its outcome. Remanufacturing is highly classified for its equivalent or better quality.

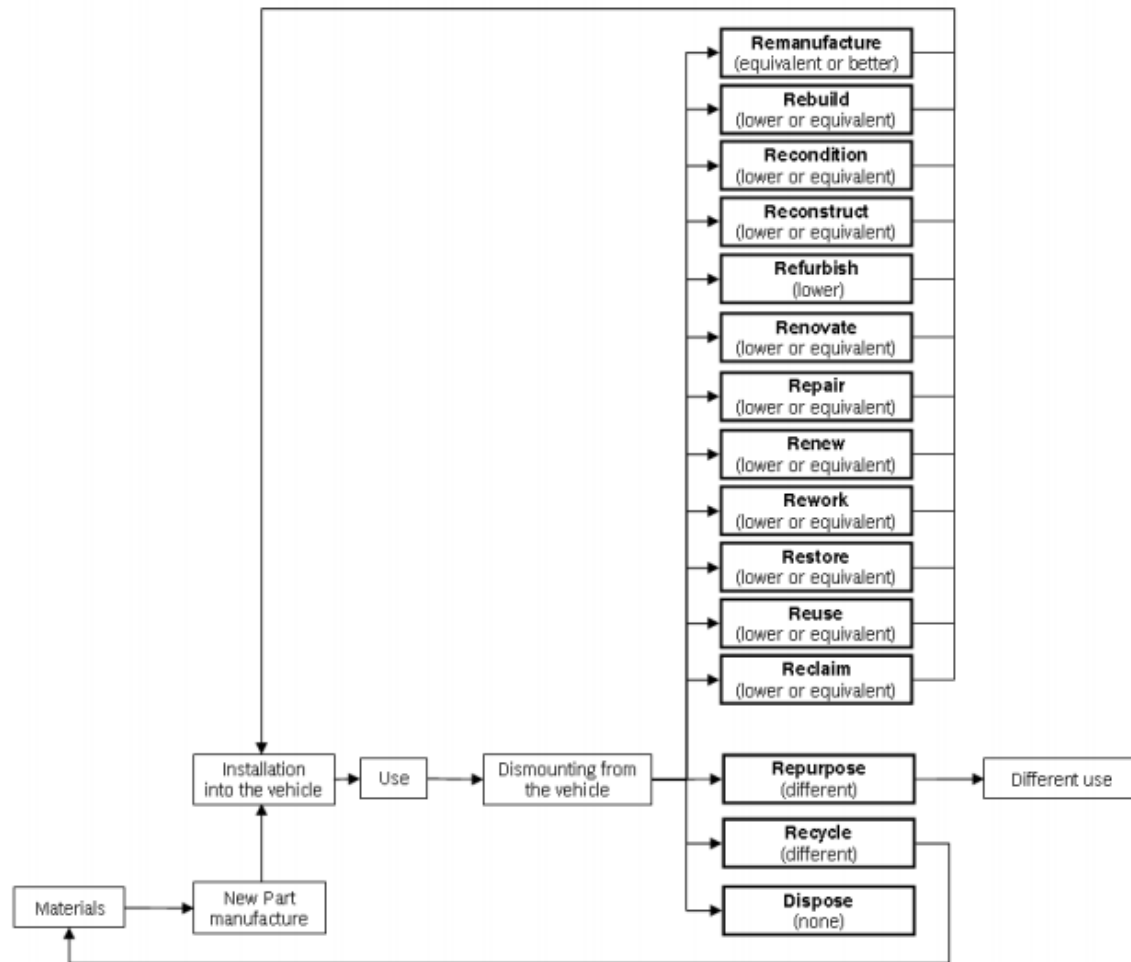


Figure 5: Different Potential Strategies of a Product and Their Quality Level by British Standard (APRA, 2012)

2.2. Remanufacturing Process

Some researchers stated essential steps in remanufacturing process when defining the remanufacturing concept. There also highlighted some characteristics in remanufacturing process that are different from manufacturing processes. Those particularities had become the major issues and discussions in the past literature. For example, there were many studies that have been conducted on the design perspective by analyzing the impact of remanufacturing process towards the product's design phase. As a result, there are some new product characteristics that have to be considered in the design phase to allow/facilitate the remanufacturing process later. Interestingly, there were specific studies done on the remanufacturing process itself, which focus on its importance. In general, the steps related to the remanufacturing process should be put in a different order or omitted, depending on product type, product condition, remanufacturing strategy,

and many more. Steinhilper (1998) illustrated the remanufacturing process based on the five key steps that are shown in Figure 6.



Figure 6. An example of a generic remanufacturing process, based on the five key steps described in Steinhilper (1998).

Figure 6: Remanufacturing Process Described by Steinhilper (1998)

Bras and Hammond (1996) have aggregated the remanufacturing steps into the following categories as the result of their reviewed literature and surveys:

- Cleaning
- Damage correction (repair, refurbishment and replacement)
- Quality assurance (testing and inspection)
- Part interfacing (disassembly and assembly)

In 2004, Sundin proposed a general remanufacturing process as shown in Figure 7, where the order of the individual operation is not specified as a consequence of the variation of the studied cases. On the other hand, Ostlin (2008) classified remanufacturing steps in a slightly different way by naming it as “The five remanufacturing phases” due to the linkage between disassembly, reprocessing, and reassembly (See Figure 8). The five remanufacturing phases are:

- a. Pre-disassembly phase
- b. Disassembly phase
- c. Reprocessing phase
- d. Reassembly phase
- e. Post-assembly phase

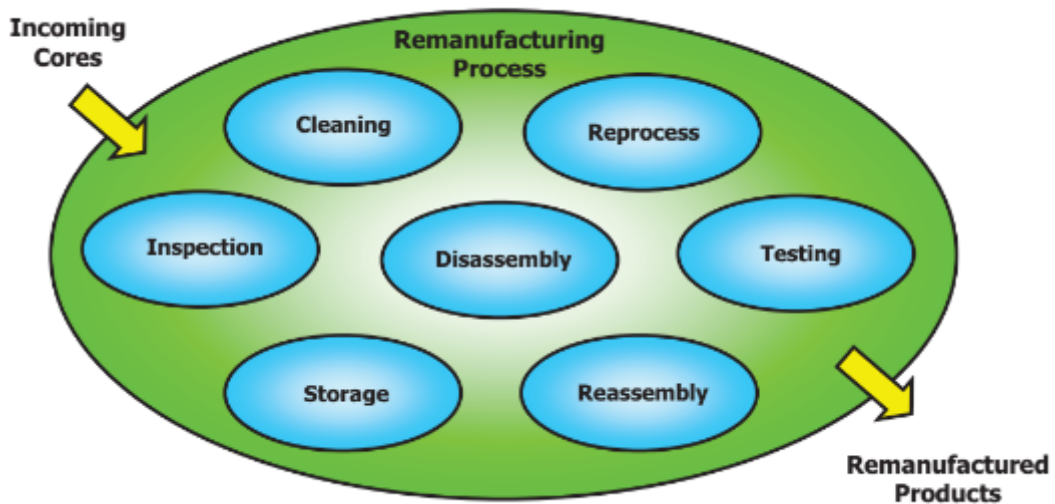


Figure 7: The Generic Remanufacturing Process by Sundin (2004)

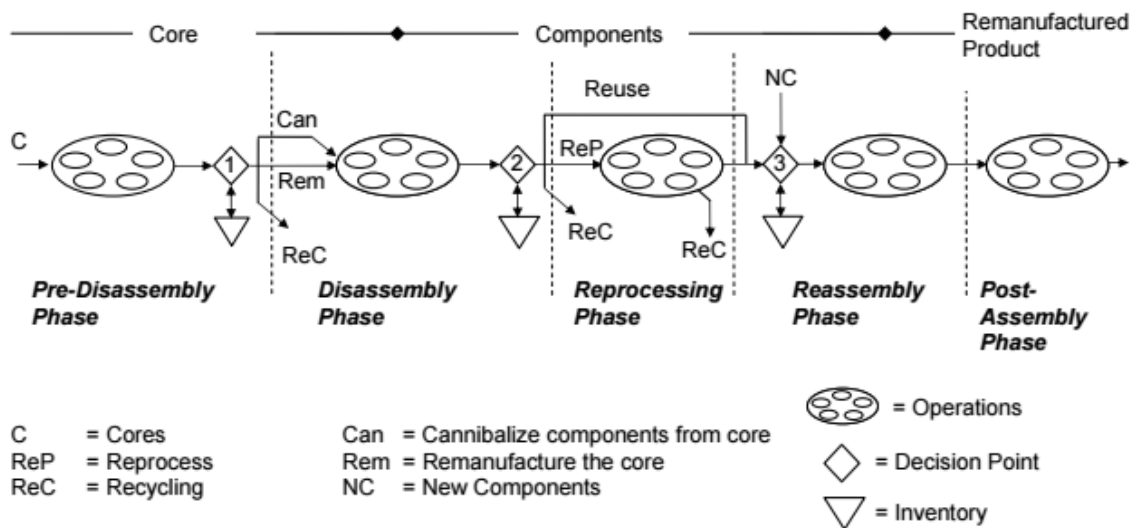


Figure 34: An overview of the five remanufacturing phases (Paper IV).

Figure 8: An Overview of the Remanufacturing Phases by Ostlin (2008)

2.2.1. Initial diagnosis

Many early studies tend to not emphasize on this phase in their literature (Guide, 2000). It is also frequently mixed-up with other inspection steps in other stages. The steps have been further improved for the importance in improving the reliability of remanufacturing process. Errington and Childe (2013) categorized this step as the first type of inspection process with the objective to immediately filter and remove cores which are

impossible and not worth being remanufactured technically and economically (Nenes et al., 2010; Errington and Childe, 2013). The steps include:

- a. Visual inspection (Nenes et al., 2010; Errington & Childe, 2013): Detecting obvious major damage that might make it unusable.
- b. Physical inspection (Errington & Childe, 2013; ERN website): Done manually or with special diagnosis equipment.
- c. Identify the part type and part number of the core (Ijomah, 2002; Errington & Childe, 2013): Used to estimate the demand and value of the product after remanufacturing and allows inventory to be managed for future use.
- d. Performance inspection (Errington & Childe, 2013): Normally use special equipment to assess the performance of the core.
- e. Basic initial cleaning (Ijomah, 2002; Liu et al. 2013): Rough cleaning to allow the determination of basic information.

The product specification is normally needed in this step. Therefore, the OEMs-remanufacturers have more advantages compared to the IR regarding this matter.

2.2.2. Disassembly

In comparison to the other closed-loop end-of-life options such as repair and refurbish, the disassembly step involved the used product (core) to be completely disassembled in its single components. Other than enabling the core to be cleaned, repaired, or replaced as desired, the disassembly step is also considered as an information gateway (Guide, 2000). The information obtained during this step is used to make decisions in various areas such as purchasing, resource planning, scheduling, shop floor control and many more. In line with the technological development, power tools are widely used by the workers during this step to facilitate the intensive tasks. In practice, workers have to inspect the components and decide whether they should be kept for remanufacturing process or discarded.

In certain cases that involve the cores that do not pass any significant cleaning, it is possible for them to have a high level of contaminant (e.g. rust, oil, dust). For the product that is not designed for disassembly, there is a high possibility for the product to be damaged during this step which increases the material replacement rates. This condition makes disassembly to be more difficult to accomplish than assembly. By integrating the

design for disassembly in the product design phase as well as coordinating the disassembly and reassembly steps, it could result on the efficiency of the disassembly process with short and responsive lead times for the overall remanufacturing process.

2.2.3. Cleaning

During the cleaning process, contaminants of the components are being removed for various objectives: (i) to facilitate failure detection; (ii) to prepare surfaces for the next process; and (iii) to make them meet the quality requirement after being remanufactured. These contaminants can be in the form of dust, oil, rust, carbonized sediment, paint residues, and many other forms. The typical cleaning methods are thermal washing, dry-blasting, wet-blasting, and ultrasonic vibration. Figure 9 presents the various types of cleaning activities which emphasize on the importance of this step in the remanufacturing activity (Liu et al., 2013). As a result, this process can be conducted in multistage and multifaceted.



Figure 9: Common Technological Process of Remanufacturing (Liu et al., 2013)

Instead of knowledge based, most cleaning in remanufacturing is performed based on the experience of the operator. This scenario has resulted to the lack of efficient solutions which contributed to higher cleaning cost, longer operation time, lower energy efficiency or higher environmental pollutions. Therefore, further studies and innovations have to be conducted to solve these problems. A study by Liu et al. (2013) has contributed to the foundation in establishing a systematic understanding on the cleaning process. In their study, there are four basic elements that have been included for core remanufacturing cleaning:

- Cleaning object: The one that needs to be cleaned in a remanufacturing process.

- Core contamination: The unwanted deposits which existed due to the effects of physical, chemical or biological actions during the core's service time and remanufacturing process (e.g. lubricating oil, antirust oil, etc.).
- Cleaning force: The force among cleaning objects, contaminants, and cleaning medium during the cleaning processes to remove the contaminants. It is classified into five categories: 1) solvency force and dispersion force; 2) surface active force; 3) enzyme force; 4) chemical reaction force; and 5) physical force.
- Cleaning medium: A medium for the cleaning environment and it has a direct contact with the surfaces that needed to be cleaned (e.g. solvent, aqueous based cleaning fluid, chemical solvent, solid particle).

2.2.4. Inspection and Sorting

This is the process of assessing and classifying the cleaned components according to their condition. The single component is classified at least into three categories: 1) reusable without reconditioning; 2) reconditionable; and 3) not reusable or reconditionable. Depending on the company's procedure, if a component has to be replaced frequently, (e.g. bearing, bushes), it has to be discarded immediately (Errington & Childe, 2013). Typical inspection activity such as visual inspection, measuring and leakage testing are being done to verify the functionality, safety, performance, mechanical condition, and geometry and surface condition. The cost and lead time were identified as the basis factors for a company in making a decision in classifying the components (Errington & Childe, 2013). This step also requires experienced employees to assess the parts and systematic information system to ensure its efficiency.

2.2.5. Reconditioning

The main objective of this process is to remove damaged components from their previous use phase and also from the secondary effects of the reconditioning processes in order to be in the condition of "like-new". Therefore, it is essential to consider the side effects of the reconditioning step to avoid any reworking. Kin et al. (2014) classified reconditioning process into five main categories based on its objectives, which are:

- Remove surface and shape defects
- Material addition or surface replacement
- Restore material properties

- Assembly and fastening manipulation
- Surface finish

For this process, the typical manufacturing techniques such as turning, drilling, milling and grinding are applied on the component based on its condition and need. There are also several steps involved in surface treatments such as spray painting, coating, chrome galvanizing, and many other steps.

2.2.6. Reassembly

When all the required (reconditioned, purchased, manufactured) components are available, the reassembly step is conducted according to the production schedule. The new same component (purchased or manufactured) might compensate the poor regeneration rates of the single component. Normally, the same assembly equipment and tools are used for this operation. Issues such as customer's demands and inventory management are closely related to this process. The reassembled product will undergo the final inspection and quality check before being packaged and distributed.

2.2.7. Final Testing

This is the final important step in remanufacturing process. In this step, functional inspection is the key part of this process where the reliability of the final product is estimated and ensured. The products that failed in the functional inspection will be reworked and retested before being sold. Practically, the failed product will be sent back to the person who reassembled it. This person will be more likely to know the possible cause of the default (Errington & Childe, 2013).

2.3. Remanufacturing System

The descriptions on every step of remanufacturing process have shown that remanufacturing cannot be represented only by the remanufacturing process itself. There are many other issues that influence the remanufacturing process which must be treated and acknowledged elsewhere in order to globally succeed in remanufacturing. Remanufacturing process only represents the internal process that happened in remanufacturing center. In order to answer this study's research questions, the information on internal process is not sufficient since remanufacturing barriers (uncertainties and complexities) occur mainly at the exterior of the remanufacturing center where the control

authority is depended on the customers. Therefore, it is essential to widen the context of remanufacturing which includes the external processes of remanufacturing process. A system is a set of interdependent elements that work together to accomplish specific objectives and to carry out a given function (Johnson, 1967). Using the “remanufacturing system” term to avoid confusion, Ostlin (2008) defined remanufacturing system as “the system for collecting used/discarded products, remanufacturing of the product, and the delivery of the remanufactured product to the customer” and the system is illustrated in Figure 10.

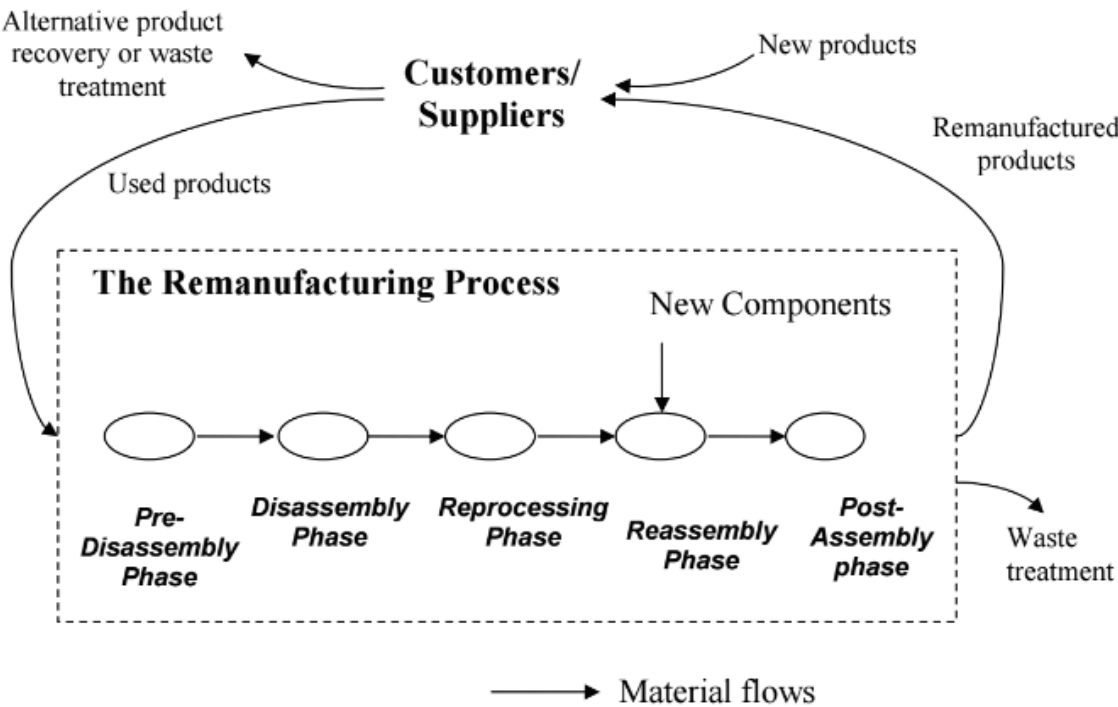


Figure 10: Remanufacturing System by Ostlin (2008)

Remanufacturing system works differently from manufacturing system due to the uncertain quality and quantity of returned cores as business input (cores) (Atasu et al., 2005; Umeda et al., 2005). These differences have resulted to the different working planning and different requirements in operating remanufacturing business. Inspired by Ostlin’s work, Barquet et al. (2013) reviewed the definition and concept of remanufacturing system and proposed a holistic view of remanufacturing system with more specific components which is presented in Figure 11. Barquet et al. (2013) listed the six elements of remanufacturing system as the following:

- a. Element 1: Design for remanufacturing
- b. Element 2: Reverse supply chain (RSC)
 - i. Sub-element 2.1: Acquisition/relationship with the core supplier
 - ii. Sub-element 2.2: Reverse logistics (RL)
- c. Element 3: Information flow in the remanufacturing system
- d. Element 4: Employees' knowledge and skills in remanufacturing
- e. Element 5: Remanufacturing operation
- f. Element 6: Commercialization of the remanufactured product

This study has chosen to use this definition to define remanufacturing system due to its comprehensiveness. This choice is aligned with the statement raised by Ferguson and Toktay (2004) on his claim that the lack of holistic perspective of remanufacturing system may hinder companies in evaluating and making decision on whether to remanufacture or not. Further elaboration is explained in the next sub-section, on the concerns and issues related to every element in order to gain a better understanding on remanufacturing and the problems linked to remanufacturing.

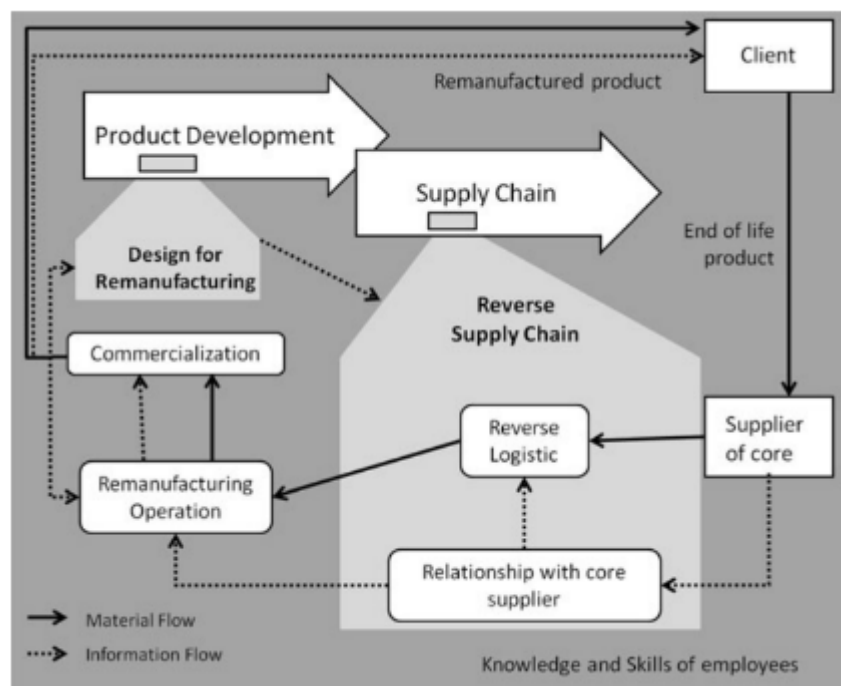


Figure 11: Remanufacturing System by Barquet et al. (2013)

2.3.1. Element 1: Design for Remanufacturing

Design is the first step in product manufacturing, which involves important decision making for the production output (Boothroyd, G., 1994). Over the decades, environment is one of the essential criteria that have to be satisfied in designing a product due to many reasons. Some of the driving factors are environmental requirements imposed by the government (Guide et al., 2003; Lindahl et al., 2006; Giuntini & Gaudette, 2003), customer's perception (Hatcher et al., 2013), and environmental awareness (Amezquita et al., 1995). In order to reduce the environmental impact of a product, manufacturer should take early precaution during the design phase since most of the impact is "locked" into the product at this stage (Lewis et al., 2001). Applying closed loop supply chain (Nasr & Thurston, 2006) and having it as one of the constraints when designing a product might be one of the solutions. Manufacturers have several options, and one of them is to remanufacture. Remanufacturing is believed to reduce more environmental impact compared to recycle in terms of value preservation (Bras & Hammond, 1996).

Design for X (DfX) is a philosophy and a methodology applied by manufacturers to develop or improve their products with a specific design aspect in mind. Under the label of Design for X, a wide collection of specific design guidelines, checklist, and software are summarized (Sundin, 2004). Each design guideline, checklist, and software addresses a particular issue that is caused by or affected the characteristics of a product. The letter 'X' stands for assembly, disassembly, environment, recycling, remanufacturing, and many more. As reported by Huang (1996), a DfX method supports the following functions:

- i) Gather and present facts about products and processes.
- ii) Clarify and analyse relationships between products and processes.
- iii) Measure performance.
- iv) Highlight strengths and weaknesses and compare alternatives.
- v) Diagnose why an area is strong or weak.
- vi) Provide redesign advice on how a design can be improved.
- vii) Predict what-if effects.
- viii) Carry out improvements.
- ix) Allow iteration to take place.

Even though DfRem can be considered as a subset of design for environment, the overall objective and benefits are significantly different (Hatcher et al, 2011). In this

dissertation, the design focus is on Design for Remanufacturing (DfRem) with respect to the environmental aspect.

Some authors stated DfRem as :

- *“Product design that facilitates any of the steps involved in remanufacture.”(Shu & Flowers, 1999)*
- *“Considering the product strategy (marketing, reverse logistics) and the detail engineering of the product in terms of remanufacture.” (Nasr & Thurston, 2006)*
- *“A combination of design processes whereby an item is designed to facilitate remanufacture.” (Charter & Gray, 2008)*

The main objective is to maintain the efficiency and the effectiveness of the remanufacturing process since the decision made during the design phase may have an important effect on the entire process (Ijomah, 2007). DfRem may also augment the remanufacturing profitability... making a product more feasible and worthwhile for the end-of-life strategy (Hatcher et al, 2011). However, there is the possibility that not all of the products are cost effective and environmentally suitable to be remanufactured (Lindahl et al., 2006; Shu & Flowers, 1999; King & Gu, 2010; King & Barker, 2007). In this case, applying DfRem seems to be indispensable especially for the original equipment manufacturers (OEMs).

However, DfRem in a deeper perspective is straightforwardly not a one concept of “design for X”. It is a combination of several “X” since remanufacturing itself consists of many processes (Hatcher et al., 2011). DfRem can be defined as a sequence of Design for Disassembly, Cleaning, Inspection, Repair and Replace, Control and Test, and Reassembly. Sundin (2004) in the “RamPro Matrix” (Figure x) identified the relation between different product properties and specific remanufacturing step. This identification is important since some product properties are needed in more than one step of the remanufacturing process in order to highlight the relevance. It is also essential to have the entire remanufacturing process in mind to avoid product properties to clash with each other when they are used for the different need in several different steps. For this case, the designer must prioritize the more critical property in performing an optimal remanufacturing process (easier and cheaper). Sundin (2004) found that the following are the most frequent properties in products that are permitted for remanufacturing process:

- i) ease of access,

- ii) ease of identification,
- iii) wear resistance, and
- iv) ease of handling.

These product properties remain the general rule for designers and it takes a lot of efforts to transform it into an applicable practice of DfRem. In the next level of understanding DfRem, it is important to answer the question on 'how one designs a remanufacturable product'. It is difficult to answer the question due to the fact that the remanufacturability improvement for every product is different. As a result, the current list of DfRem guidelines is rather general (Hatcher et al., 2011). Ijomah et al. (2007b) classified the DfRem guidelines into features that facilitate remanufacturing and features that hinder remanufacturing. Besides that, Amezcuita et al. (1995) listed some of the guideline in improving the design of an automobile door for remanufacture. He concluded that remanufacturable product must have robust parts (Lund,1984), corrosion resistant, and durable (Statham, 2006; Lund, 1984; Ijomah et al., 2007a; Nasr & Thurston, 2006). There were also other researchers who highlighted other important general guideline for DfRem: i) the product must be a core (Statham,2006; Lund, 1984;); ii) it has to be technologically stable (Statham, 2006; Lund, 1984); iii) its original function can be restored inexpensively (Lund, 1984; Ijomah et al., 2007a); iv) it should be repairable and replaceable (Statham, 2006; Lund, 1984); and v) it is capable of being disassembled without causing too many damage (Statham, 2006; Lund, 1984). However, there are also many key determinants of remanufacturability that could not be controlled by the designer, including legislation, demand, fashion, and manufacturers' prohibitive practices (Ijomah et al., 2007a).

Although many agreed on the importance of applying DfRem early in the design stage, it is undeniable that the information on how to make a product remanufacturable is minimal (Amezcuita et al., 1995). Therefore, many researchers focused on developing DfRem tools and methods to help designers and manufacturers in the early design stage and also throughout the remanufacturing process. These tools and methods exist in the form of mathematical model, software tools, and static references (Hatcher et al., 2011). However, there are limits on how far these tools and methods could be applied in the industry (Nasr & Thurston, 2006). The complexity of these tools and methods, the lack of lifecycle thinking, and the fact that OEM may have their own tools and methods have contributed to this question (Hatcher et al., 2011). Therefore, there are researchers who proposed other type of

tools and methods by using the existing design approach concept such as modularisation and QFD (Quality Function Deployment) which are believed to be more common for the industry. Goodall et al. (2014) classified tools and methods into two types: i) tools and methods to help in the decision-making; and ii) tools and methods in optimising remanufacturing process. This classification might help on the understanding for each type of tools and methods that could be used for improvement and analysis. The detailed descriptions on tools and methods are discussed in Chapter 4.

Another interesting issue in this topic is how to integrate DfRem into a company's design process. The previous discussion has mentioned that the failure to acknowledge this issue might be the reason that DfRem methods and tools are hardly used in the industry. Many DfRem literatures only focused on technical aspect and overlooked operational issues such as management, motivation, and communication (Hatcher et al., 2014). Hatcher et al. (2014) proposed DfRem integration network model which takes into account the external and internal operational factors of a company as an effort to overcome this issue.

2.3.2. Element 2: Reverse Supply Chain

Guide and Van wassenhove (2002) defined reverse supply chain as a sequence of essential activity to retrieve a used product, starting from the product's end-user, and followed by various options of the end-of-life strategy (reuse, remanufacturing, recycling, or disposal). There are many reasons for companies to apply reverse supply chain. Some companies do it for a necessity reason like respecting the government legislations (European end-of-life Vehicle (ELV) Directive, the Waste Electrical and Electronic Equipment (WEEE) Directive within the European Union, and the Electronics Recycling laws in the U.S), or dealing with consumers' environmental awareness. There are also companies that voluntarily do it by choice as a result of realizing the benefits of product recovery practice (IBM, Fuji Xerox, Kodak - Ayres et al., 1997).

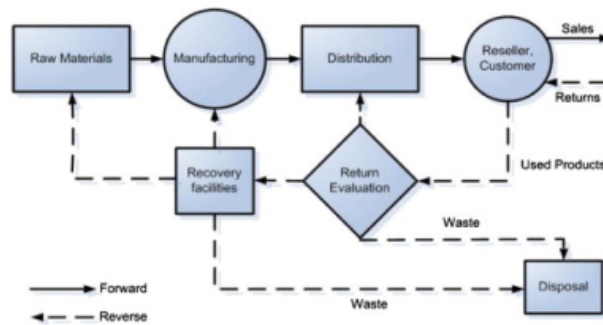


Figure 12: Generic Form of Forward/Reverse Logistics (Tonanont et al., 2008)

Figure 12 demonstrates a simplified schematic of a generic form of forward/reverse logistics (Tonanont et al., 2008). Despite its benefits, RSC is a complex structure and this study intended to discuss the reverse supply chain in remanufacturing practice. Barquet et al. (2013) described that RSC has two sub-elements:

- Acquisition/relationship with the core supplier: Normally discuss information flows and the related issues.
- Reverse Logistic (RL): Discuss material flows and related issues.

i. Acquisition/Relationship with the Core Supplier

Hammond et al. (1998) had conducted a survey on 28 automotive remanufacturers and found that the major difficulty encountered by them in remanufacturing product was parts availability (43% of the responses) and core availability (14% of the responses). There are several issues regarding this concern and one of them is the lack of cross referencing for aftermarket part supplier. A research by Ostlin J (2008) investigated the relationship between customer (core supplier) and remanufacturer, and has identified seven different types of structural relationships, which are:

- Ownership-based: The product is owned by the manufacturer and operated by the customer. The control of the installed products is high and normally regulated by contracts with different options: rental, lease or product-service system offer.
- Service contract: Based on a service contract between manufacturer and customer which includes remanufacturing.
- Direct-order: The customer returns the used product to the remanufacturer; then, the product is remanufactured and the customer gets the same product back (if it is possible to perform a remanufacturing operation).

- Deposit-based: When customers buy a remanufactured product, they are obligated to return a similar used product. Indirectly, they become the supplier to the remanufacturer. This type of relationship is common in the automotive industry.
- Credit-based: When customers return a used product, they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.
- Buy-back: The remanufacturer simply buys the desired used products from a “supplier”, which can be the end user such as a scrap yard or something similar, or a core dealer.
- Voluntary-based: The supplier gives the used products to the remanufacturer. The supplier can either be a customer or not.

This research highlights the importance of relationship management between supplier and remanufacturer with a proposition of a closer and more beneficial relationship as a recommendation to achieve an efficient remanufacturing activity (Barquet et al., 2013; Matsumoto & Umeda, 2011).

A good relation with the suppliers could gain a lot of benefits. One of them is the ability to pre-assess the remanufacturability of used products at the customer’s place before transferring it to the remanufacturing company to avoid unnecessary transportation (Ferrer & Clay Whybark, 2000; Barquet et al., 2013). The unremanufactured products are then being recycled locally to reduce cost, energy, and environmental impact (Ferrer & Clay Whybark, 2000). Thus, it is essential to have clear expectations about returns and to encourage employees to handle the cores carefully when they reach a remanufacturing process (Barquet et al., 2013). Therefore, it is worth to establish a special team with appropriate skills to handle the potential used products suppliers (Barquet et al., 2013).

ii. Reverse Logistic (RL)

While the first sub-element focuses on the relationship with the core supplier, the second sub-element concentrates on “the process of planning, implementing, and controlling the product efficiency, cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing the value or proper disposal (Rogers & Tibben-Lembke, 1998). The Reverse Logistics Association defines reverse logistics as “all activity associated

with a product/service after the point of sale, with the ultimate goal to optimize or make more efficient aftermarket activity, thus saving money and environmental resources” (Reverse Logistic Association,).

With reference to these definitions and also the definitions mentioned beforehand, planning a reverse logistic for remanufacturing process is not an easy task (Barquet et al., 2013). S. Chopra and P. Meindle (2007) listed six supply chain drivers that must be considered in managing reverse logistic, which include:

- Facilities : Physical location where product is stored, assembled, or fabricated. The decisions regarding the role, location, capacity, and flexibility of facilities have a significant impact on the supply chain's performance.
- Inventory: All raw materials, work in process, and finished goods within a supply chain.
- Transportation: Moving inventory from point to point in the supply chain. It can take the form of various combinations of modes and routes.
- Information: Data and analysis concerning facilities, inventory, transportation, costs, prices, and customers throughout the supply chain.
- Sourcing: The choice of the person who will perform a particular supply chain activity.
- Pricing: Determines how much a firm will charge for goods and services that are available in the supply chain.

Furthermore, the uncertain parameters such as price, demand, costs, products' return rate, return time, quality of return products, and various risks (Govindan et al., 2015) have added the complexity in planning an efficient remanufacturing operation. It is believed that short cycle time, forecasting, accurate information system, and good RL planning can reduce uncertainties (Lacerda, 2004).

Transport and packaging can be another challenging issue for remanufacturing. Products in a proper packaging are transported in a large volume from manufacturer to a few customers in direct logistic. However, this is not the case for RL. Scattered supplier locations, mix cores type and condition with a low volume and without packaging may generate complication and increase cost (Ferrer & Clay Whybark, 2000; Ballou, 2006). In a different scenario, cores can be gathered in a centralized warehouse/store and installed locally near suppliers' locations. However, the products might have to stay longer in reverse

channels and resulted in the increase of the final RL cost. For storing and packaging, Ferrer and & Clay Whybark (2000) introduced some detailed propositions as solutions such as the use of a standardize, flexible and reusable container for packaging, the use pallets for large cores, and also simple form and practical locking system.

2.3.3. Element 3: Information Flow in Remanufacturing System

Information flow plays an important role in dealing with remanufacturing process uncertainties (Barquet et al., 2013). An effective information flow management can lessen uncertainties and can help to create structural remanufacturing system (Barquet et al., 2013). Kurilove (2013) was able to distinguish the information flows between forward information flows and reverse information flows. For better understanding, Figure 13 shows the position of both information and their relation towards other elements of product life-cycle (Lindkvist & Sundin, 2013). As shown in Figure 13, information flow is strongly related to material flow and it is not easy to manage these flows.

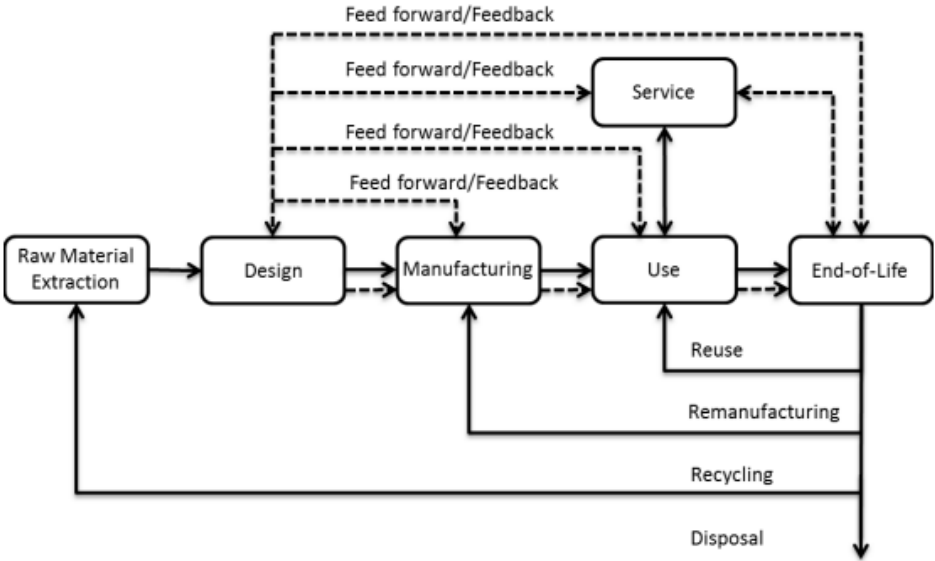


Figure 2: Product life-cycle information flows of a generic product life-cycle. The solid arrows represent material flow, whilst the dashed arrows represent information flows.

Figure 13: Information flows and material flows of a generic product life-cycle. The solid arrows represent material flow, whilst the dashed arrows represent information flows (Lindkvist & Sundin, 2013)

Information can be objective (ie:product characteristics, performance) or subjective (i.e.: customers, company staffs' opinions) data. Thierry et al. (1995) classified four categories of general required information related to remanufacturing:

- i) Information on the composition of products including physical characteristic, remanufacturing feasibility, and legislative requirements.
- ii) Information on the magnitude and uncertainty of return flow including return flow characteristics, law, and type of contract etc.
- iii) Information on markets for remanufacturing products including information on level of customers' acceptance of these products.
- iv) Information on actual product recovery and waste management operations including analysis on the organizations involved, obstacles, volume of remanufactured products, costs and revenues, and the overall environmental impact of remanufacturing activity

In order to help companies managing this issue, Guide (2000) identified seven complicating characteristics related to information flows for remanufacturing production planning and control system, such as the following:

- i) Uncertainty in timing and quantity of returns
- ii) Balancing returns with demands
- iii) Disassembly of returned products
- iv) Materials recovery uncertainty
- v) Reverse logistics
- vi) Materials matching
- vii) Stochastic routings and highly variable processing time

The information flows of a company exist internally and externally. It is an obligation to put some effort to improvise both aspects. Internally, companies can encourage information and knowledge exchange among different departments (Goh & McMahon, 2009). Externally, Barquet et al. (2013) and Lindkvist and Sundin (2013) suggested companies to collaborate with remanufacturing stakeholders as well as establishing communication throughout the remanufacturing process including collecting feedbacks. The collection of Feedbacks is important to improvise future product and process (Ferrer & Clay Whybark, 2000). All information should be gathered in a coordinated way to facilitate information usage and analysis (Roberts & Clarke, 1989). In order to achieve the mentioned objectives, companies should utilize existing tools and methods (Goh & McMahon, 2009).

2.3.4. Element 4: Employees' Knowledge and Skills in Remanufacturing

It is believed that remanufacturing industry has the potential to create more jobs for local people (Steinhilper, 1998) due to the diversity of its process. From a general to a particular task, it is essential for employees to adapt to the system and act correctly towards the need of every stage (Barquet et al., 2013). According to Lund and Hauser (2010), in the USA, the labour cost could range from 34% to 45% of the overall product value; this makes it the major aspect in remanufacturing industry. In all product sectors, half of their employees are classified as skilled labour, 30% are semi-skilled, 10% are unskilled, and 10% are professionals. According to sector, office furniture remanufacturing requires the fewest skilled workers while automotive parts and electrical appliances sectors demand the highest proportion of skilled labour (Lund & Hauser, 2010). Hammond et al. (1998) had conducted a survey on automotive parts sector, and found that the sector faced problems on employees' skills that dominate the three categories of remanufacturing process – inspection, repair, and reassembly. The reason for the occurring problems is due to the abundance of product parts that has to be familiarized by the employees as well as the complicated and diverse repairing and assembling technique. For the inspection phase, it is challenging to find a qualified person who can define the quality standard of a “good” product from remanufacturing yield.

Many researchers have suggested the best solution for this problem is to educate and train the employees (Ferrer & Clay Whybark, 2000; Liu, 2013; Barquet et al., 2013, Jacobsson, 2000). Jacobsson (2000) proposed that employees should be trained to handle the variable and uncertain quality and quantity of cores as their conditions are difficult to be predicted. Therefore, it is also important to train them to possess a good quality of consciousness and vigilance (Lund,1984). Preferably, they should be given the training by the company itself on the specific operation to familiarize them with the workplace environment (Barquet et al., 2013). The employee does not necessarily need to be qualified as it is believed that a non-qualified person is able to think outside the box to come up with a new solution (Hermansson and Sundin, 2005).

2.3.5. Element 5: Remanufacturing Operation

A remanufacturing process follows a certain system that consists of the following steps: disassembly-cleaning-inspection-reprocess-reassembly (Lopez Ontiveros, 2004;

steinhilper, 1998). However, Sundin (2004) has formulated a general remanufacturing process as shown in Figure 7 (in page 29). Besides that, Sundin (2004) also introduced a non-specific order of the individual operations as a definition of a general remanufacturing process. This is due to the different sequences of remanufacturing operations applied by remanufacturing company depending on several factors such as type of product (Ijomah et al., 2007), product design, working environment, remanufacturing strategy, and product volume (Sundin, 2004).

However, Ostlin (2008) affirmed that disassembly-reprocess-reassembly order remains valid and divided remanufacturing process into the following five phases:

- Pre-disassembly phase: Preparatory phase before disassembling product. It includes inspection, cleaning, and storage, depending on the company.
- Disassembly phase: The phase involving products being totally disassembled. It consists of several activities/steps. A decision must be made whether to remanufacture a component or not.
- Reprocessing phase: The objective is to boost the quality of components/products.
- Reassembly phase: Where the individual components are being reassembled. It can be the reprocessed components, a new component, or a reused component. The new component can either be from the same model or the upgraded version.
- Post-assembly phase: The phase that comes after the reassembly step finishes. The product is put under working state to test the functionality and performance. Other activities can also be performed such as painting, upgrading software, and packaging.

This process deals with many decision-making and each decision made will affect others and vice versa. The decision-makings in the earlier stages are more crucial in directing the further remanufacturing process of a product than the later stages (Ostlin, 2008). Even though economic plays a major role in influencing decision making (Ijomah,n.d.), remanufacturer should not overlook the environmental and the social factors. These three pillars of sustainable development in the context of remanufacturing will be discussed in the following chapter.

In their study, Lundmark et al. (2009) found that complexity and uncertainty are the most challenging factors in remanufacturing which occur in the remanufacturing process. The factors could lead to inefficiency and increased costs (Schuh, 2005 as cited in Haumann et al. 2012). Complexity is determined by the number and diversity of elements and

relationships that occur in this system as well as their temporal variability (Schuh, 2005 as cited in Haumann et al. 2012). For the case of uncertainties issue, it involves cases such as uncertainties of core supply, market demand, and cores condition that complicate the decision-making and the process itself. To overcome the mentioned problems, remanufacturer can plan their remanufacturing process using remanufacturing tools and methods specifically for process optimisation (Ostlin, 2008; Ismail, 2014). From experience, some remanufacturers forecast their component recovery rate (Ostlin, 2008; Barquet et al., 2013) which includes observation, data record/inventories (Statham, 2006), prediction, and projection activities (Chambers et al, 1971).

Since cleaning is believed to be among the most demanding steps in remanufacturing (Liu et al., 2013), Liu et al. (2013) have done a study that focuses on cleaning technology for remanufacturing process. A substantial knowledge in cleaning technology is essential to optimize the process. The detailed steps and guidelines are available in their research and they become one of the most studied methods in Chapter 4.

2.3.6. Element 6: Commercialization of the Remanufactured Product

This element consists of sales, distribution, market, relation with customers/clients, service after-market, advertising, and promotion of remanufactured product. It is an essential factor in remanufacturing sector and becomes one of the strongest remanufacturing drivers as stated by Ijomah et al. (2007a):

“Remanufacturing is only appropriate when there is a market for the remanufactured product.”

However, not many people know how to commercialize remanufactured product or how to reach their potential clients (Jimenez-Para et al., 2014) which generates barriers to the viability of remanufacturing efforts, “no matter how well the operational system is designed” (Guide Jr et al. ,2009).

In order to define which product is suitable for remanufacturing from marketing perspective, it is important to take into consideration some of these factors: type of product, consumption patterns, customer’s perception, intellectual property and antitrust issues, and behaviour of the consumers (Statham, 2006; Jacobsson, 2000; Hamzaoui-Essoussi & Linton, 2014). An example of an unsuitable product for remanufacturing is fashion-affected product because users may prefer brand-new products without considering the quality and cost of

the remanufactured alternative (Ijomah et al., 2007a). On the other hand, products whose functions are prioritized by customers are well-suited for remanufacturing (Jacobsson, 2000). The lack of information and familiarity about remanufactured product could lead to low perception among customers. This barrier has resulted in the difficulty to commercialize the product as customers' willingness to pay less (Hamzaoui-Essoussi & Linton, 2014). Consumers' behaviour such as the preference of something new for their lifestyle choice may hinder remanufactured product sales (Ijomah et al., 2007).

Remanufactured product can be commercialized in several different ways. It can be sold or leased to clients. Besides that, remanufactured product can also be used as a replacement product for warranties or being sold for their functionality in Product Service System (PSS) business model (Barquet et al., 2013). The cheap price of remanufactured product has always been the main attraction for clients, and this can cannibalize the sales of new products. Ovchinnikov (2009) stated that companies have to balance the additional revenue from selling remanufactured products, the demand cannibalization of new product sales, and the cost of remanufacturing process while making the decision to remanufacture. The majority of companies differentiate the distribution channels of remanufactured products and the new ones. For example, Dell has another Web site (www.delloutlet.com) which is used to sell its remanufactured products (Ovchinnikov, 2009).

On the other hand, Subramanian and Subramanian (2012) examined the influence of seller reputation, remanufacturer identity, and warranty strength towards remanufactured products' prices. Using the data on eBay, they found that the seller's reputation of remanufactured products as well as their identity (OEM/authorized remanufacturer/third party) has a significant price differential between corresponding new and remanufactured products. In contrast, they found that warranty strength has no significant effect on the observed price differentials. However, other researchers have reported mixed findings on the relationship between warranties and product price. For example, Pavlou and Dimoka (2008) found a positive relationship between warranties and prices, whereas Dewally and Ederington (2006) found no statistical evidence for this relationship.

Several researchers have proposed several suggestions to elevate the sale rate of remanufactured product. Ferrer and Clay Whybark (2000) proposed several suggestions, including efforts on developing market awareness, appreciation and acceptance among employees and customers, warranty and extra service consideration, the research on finding

a convincing price, and developing means for customers to send feedback. Statham (2006) emphasized remanufacturers to study and understand their market, avoid misconception on remanufactured product, and make follow-up calls to measure their product's performance. PSS appears to be an encouraging approach in commercializing remanufactured product through leasing or selling its functionality, and companies are suggested to apply it.

2.4. Remanufacturing and Sustainable development

Remanufacturing was applied solely for economic reason in the past, especially in the US. As a result of the growing environmental awareness, the primary driving factors for companies to remanufacture in the recent years are ecological and legislative (Amezquita et al., 1995). Since remanufacturing deals with human (workers, clients), it is compulsory to consider the social aspect in remanufacturing in order to create a bearable social condition. These three aspects (economic, environmental and social) are the three pillars of sustainable development which provides an approach to make better decisions on the issues that affect our lives including remanufacturing.

Sustainable development is derived from the Brundtland report in 1987 as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Since then, this concept has been developed to achieve the goal of socially inclusive and environmentally sustainable economic growth. At the Earth Summit conference in 1992, an action agenda named Agenda 21 had stressed the need to change the way of doing business in order to integrate environmental and social concerns at all development processes. Since everyone functions as a user and information provider in sustainable development, it is important to involve multi-stakeholders in problem solving and decision-making processes with respect to issues and plans that affect them. The pillar of sustainable development has been expanded by some authors to include the fourth pillar, which is the pillar of culture, governance, institutions, etc. Since technical factor affects the decision-making and process in remanufacturing, Fatimah et al. (2013) have added the technical pillar in addition to the classic pillars of sustainable development (see Figure 14). This addition permits designer to address specific technical requirement in making decision for remanufacturing planning and process. The elaborations for all pillars are shown in the following diagram.

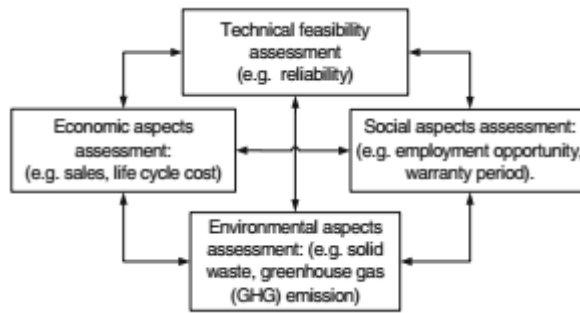


Figure 14: An Integrated Framework of Sustainable Development (Fatimah et al. 2013)

2.4.1. Remanufacturing from Economic Perspective

In general, the benefits of remanufacturing from economic perspectives can be in the following forms:

- Material and energy savings which can reduce the purchasing and processing cost by reusing the used component.
- It can lessen the economic costs of waste disposal (Kopicki, 1995).
- It can be used as a marketing tool by companies to differentiate their products and services. (Debo et al., 2005)
- A greater range of product choice is available to the buyer, and the lower prices stimulate competition from new product manufacturers (Lund, 1984).

However, further profound analysis must be conducted by companies before deciding to remanufacture in order to ensure their company's economic viability and profitability. Therefore, the analysis must take into account many factors such as logistics, production planning, and inventory control (Fleischmann et al. 1997) suited the company's type (OEM or third-party remanufacturer).

Another main requirement for remanufactured product is having enough market supply and demand (Kerr & Ryan, 2001). Michaud and Llerena (2006) linked this issue with consumer behaviour and beliefs, particularly on the factors that lead consumers to bring back their end-of-life products and purchase remanufactured products. Analysis of return behaviours shows that consumers need to be informed about the used product's value and about possible collection structures. Another solution is to use the various incentive approaches to motivate more used product to be returned to the company. For the consumers' purchase behaviours, the analysis emphasizes the importance of remanufactured products marketing. Remanufacturing aims to have quality equivalent to a new product, and environmental-friendly purchase is suggested as the marketing contents.

The main economic challenge of remanufacturing is uncertainties (Guide, 2000; Govindan et al., 2015). Graham et al. (2015) listed several significant uncertainties from business perspective such as uncertain quantity, time and condition of product supply, uncertain product demand, and uncertain logistic time and costs. In order to overcome the challenges, it is important for a company to build a specific knowledge and capabilities besides having a good company organization. Capabilities and knowledge gained from accumulated experience are somehow important without denying the importance of economics theories (Michaud and Llerena, 2006). Companies have to take into account the issues and solutions for long term investment for remanufacturing.

2.4.2. Remanufacturing from Social Perspective

Social equity has been one of the main concerns for most of the past 150 years (Dyllick & Hockerts, 2002). To have a better understanding on social term, Dyllick and Hockerts (2002) divided social aspect into two categories, which are the human aspect and the societal aspect. Some of the examples for human aspect are skill, motivation, and loyalty of employees and customers, while societal aspect includes the quality of public services.

One of the social benefits of remanufacturing is employment opportunity. Employment opportunity could mitigate poverty and enhance social equity by reducing the gap between the rich and the poor (Biswas et al., 2001). Remanufacturing process normally consists of labour intensive activities which are not only handled by skilled workers (Parkinson & Thompson, 2003; Gray & Charter, 2007), but also for the semi-skilled workers (Lund, 1984) depending on the product type and task. Workers are able to gain skills and trainings that can lead to higher-paying jobs (Lund & Hauser, 2010). Another aspect to be noted is the safety aspect since remanufacturing process normally exposed the workers to risky tasks of disassembly activity and potential interaction of hazardous substances. Remanufacturer must ensure the safety of the workplace and local residents (Dowlatshahi, 2005; Presley et al., 2007).

From consumer's perspective, remanufacturing offers low cost alternative of 30-40 percent less than new products (Giuntini and Gaudette, 2003). This is interesting especially for the lower income segment. When remanufactured product has its own potential customers, the sale of new products might not be affected (Rathore et al., 2011). In the recent years, a growing phenomenon of global industrialization which involves less

developed country to obtain the “older technology” with a “cheaper” price has created another drive for remanufacturing industry (Lokhande et al., 2014).

Consumers are also concerned on the issue of warranty. It represents one of the corporate social responsibilities of an industry (Anityasari & Kaebernick, 2008). Consumers may be concerned about product’s durability, maintenance cost, and the longevity of remanufactured product (Ferrer & Clay Whybark, 2000). Thus, warranty plays a big role in ensuring that the performance of remanufactured product is also as good as new product. For remanufacturer, warranty means potential additional cost. The warranty’s importance and options for the OEM were carefully discussed by Lokhande et al. (2014).

2.4.3. Remanufacturing from Environmental Perspective

Environment consists of all occurring surroundings and conditions where living things grow and interact on Earth such as plants, animals, air, water, climate, et cetera. Manufacturing industry has been one of the important factors that caused environmental degradation (Tyagi, 2014). Parallel with the increasing awareness on this issue, reactive pressures (i.e.: governmental and legal policies) and proactive pressures (i.e.: developing company competitiveness) have been influencing manufacturers’ strategic decisions and directions. This has resulted in a more environmentally conscious business practice and management (Sarkis, 1998).

The implementation of closed loops end-of-life activities including repair, recycle, and remanufacture are among the practical actions taken by companies. The end-of-life hierarchy by Sundin and Lee(2012) (See Figure 15) can be referred to get some general overview on the end-of-life activities and their environmental impacts. From the diagram in Figure 15, the surface of each pyramid section signifies the environmental impact generated by each end-of-life option. Remanufacturing is situated at the third level from the top, and it is more preferred than recycling from the environmental impact point of view.

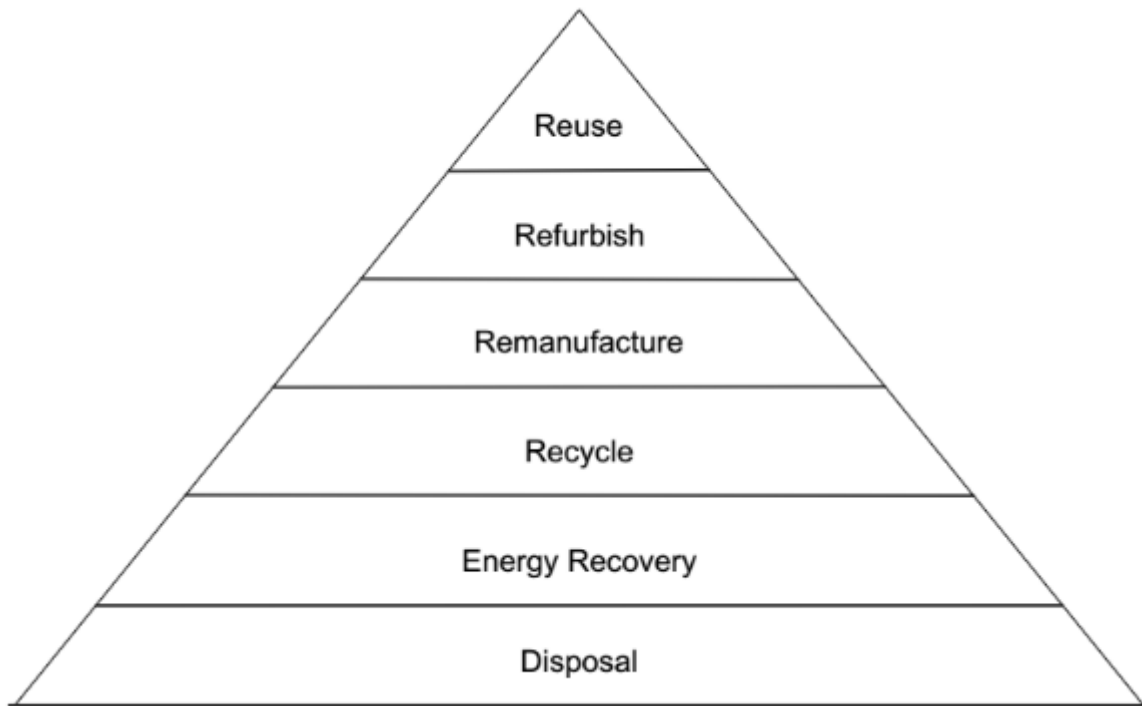


Figure 15: End-of-life hierarchy (Sundin and Lee, 2012)

Sundin and Lee (2012) had summarized twelve comparative environmental studies on remanufacturing between year 2000 to 2010. Currently, there are at least eight other studies published on this issue with different products and analysis methods. The mentioned studies were mostly comparing the environmental performance of remanufactured products and the manufacturing of new products. This is normal since the end product of those scenarios are similar and comparable (Lindahl et al., 2006). Besides that, Lindahl et al. (2006) have given suggestion to insert the recycled material in the newly manufactured product in order to make remanufacturing and recycling scenario comparable. If this was the case, more element like transports from the local recycler must be added, which will make the study more complicated.

There are many ways to conduct environmental studies on remanufacturing, and there are many factors that influence the obtained results. Sundin and Lee (2012) distinguished the measurement method into two categories. The direct method measures materials and energy consumption and waste generation which will be translated directly to resources savings. This method is arguable because each material does not represent the same impact on the environment. Some materials are either more precious or more harmful

than others. Several studies converted this measurement to carbon dioxide which is equivalent with a common indicator for comparisons and communication reason. The other category is the indirect method, which applies the Life Cycle Assessment (LCA) methods to assess the environmental impact. This method is believed to provide more insights and accurate information on the potential environmental impact. However, this method can be too tiring and time consuming to be conducted (Amaya et al., 2010).

Majority of the recent studies used the indirect measurement method. Thus, the other factors that may greatly affect the final results revolve around the LCA preliminary phase. It is important to carefully defined issues such as functional unit, system boundaries, assumptions, and limitations. Besides that, the selection of impact categories and life cycle interpretation are also crucial in justifying and communicating the remanufacturing benefices. Since there is no standard procedure to quantify the environmental benefits of remanufacturing, the existing studies were normally based on LCA guidelines that are rather general (Sutherland et al. 2008, Sundin and Lee, 2011).

Results obtained by Four Elements Consulting (2008) demonstrated that remanufacturing had less environmental benefits compared to new production. These results are due to the assumptions that they include in their system boundaries. In these cases, Four Elements Consulting took into consideration the use phase of both studied cartridges and assumed that the quality of remanufactured cartridges is less and more papers were needed to replace the faulty copies. This is in contrast to some studies that neglected the use phase by assuming that the quality of remanufactured products remain the same (Lindahl et al., 2006; Amaya et al., 2010). This example shows the importance of defining system boundaries that can affect the overall results.

The energy saving issue in the use phase of remanufactured products has been well addressed and discussed by Boustani et al. (2010), Gutowski et al. (2011), and Smith and Keoleian (2004). They highlighted that a small decrease in efficiency of powered remanufactured products would overwhelm and negate the benefits during the next use phase. Therefore, product design that uses modular platform has been suggested to allow upgrading, and in this case, it should incorporate energy efficiency improvements. In addition, Kerr and Ryan (2001) have proven that a modular photocopier has greater reductions in resource consumption and waste generation compared to the classic photocopier design.

Most of results from previous studies showed that remanufacturing is a preferable option compared to new manufacturing in certain environment indicators and impact categories. For example, Xerox remanufactured photocopiers are expected to save at least 19% of water consumption, 23% of CO₂ equivalents, 27% of energy consumption, and 35% of materials consumption and landfilled waste (Kerr & Ryan, 2011). Besides that, a new Electrolux AB washing machine produces 60 times higher greenhouse gases emissions and needs 30 times more energy in production, compared to a remanufactured washing machine (Lindahl, 2006). A study by Goldey et al. (2010) indicated that a remanufactured telecom equipment saves at least 30% of the global warming potential (GWP, kg CO₂eq) calculated by the LCA, compared to a newly manufactured product. However, it is unsafe to make it as a general conclusion since remanufacturing is often dependent on the context (Lindahl et al., 2006).

2.4.4. Remanufacturing from Technical Perspective

Remanufacturing systems have a high level of uncertainty and complexity if compared to the traditional production systems. In fact, companies that are involved in remanufacturing activities have to face a series of problems that limit the efficiency of their production process. Most of these uncertainties are associated to the technical aspect. Guide (2000) has identified several technical and management issues such as the following:

- difficulties in disassembling of the product;
- uncertainty about the quality of returns;
- difficulties in matching the parts;
- uncertainty in working cycles and processing times;
- lack of correlation between returns and demand;
- uncertainty in quantities and timing of returns;
- and configuring and managing a reverse logistics network.

These technical and management issues are affecting remanufacturing feasibility, and they must be given sufficient thought and consideration in planning and control system.

Besides the classic sustainable development factor, the technical aspect also plays a critical role in remanufacturing planning and decision making. A product might meet the economic, environmental, and social requirements, but it has the probability to pose low remanufacturability if the company failed to consider the technical aspects during design

and planning process. From the stated reasons, this study has chosen to treat technical issues separately for better remanufacturing results.

2.4.5. Conclusion and Research Question 1

After reviewing previous studies, this section deduces the first research question of this dissertation. As presented earlier, many studies focused on the economic and technical issues of remanufacturing process. From time to time, there have been more and more studies that considered the environmental aspect as the new added value offered by remanufacturing activity. However, there were a few studies that mentioned the social aspect in the remanufacturing sector. The social aspect might come from the pressure to achieve sustainable development requirements. These three aspects (economic, environmental, and social) are the three pillars of sustainable development concept, which is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Waheed et al., 2009). This concept has emerged as the development catchphrase over the past few decades. Both national and international organizations have given serious attention in detailing and interpreting this concept, including industrial sector. Many companies have been using this concept as a benchmark for quality and promotion reason.

Meanwhile, remanufacturing has also been viewed from its process perspective. Many studies are discussing issues that revolve around remanufacturing process (remanufacturing process is defined as a process that starts from disassembly and end with final test). Some studies only focus on the reverse supply chain which influences the efficiency of remanufacturing activity. Besides that, there were also studies that analysed the market demand for remanufactured products. These are some of the components of remanufacturing activity that might be larger than what other perceived. The broad definition of remanufacturing system makes it more difficult to ensure its sustainability.

Moreover, in the effort to ensure the remanufacturing and sustainable development objectives could be achieved, details on remanufacturing process from top to bottom must be well-planned and observed. A bad decision in operation and decision might give negative results and contribute to the failure to overcome the current problem on resource constraint and waste management. However, the broad process in planning remanufacturing is not the only challenges in the industry. The process is also complex and uncertain. Therefore, a well-

guided remanufacturing planning and decision-making process, which integrates sustainable development concept is viewed as a relevant and needed subject to be explored and discovered. This study intended to propose a solution from design perspective in order to answer the first research question of **“how to characterize remanufactured product and remanufacturing system for sustainable development perspective?”**

2.5. Design for Remanufacturing (DfRem) Tools and Methods

From our point of view, the above propositions are not sufficient to help designers. The richness of knowledge, the technology advancement, and the competitive business scenario can change companies' working culture. The application of remanufacturing tools and methods in companies has become essential for more accurate results, shorter working duration, and earlier work planning. Therefore, it is significant to conduct a study on remanufacturing tools and methods with the objective to help designers to plan remanufacturing. This chapter will review one of the significant research areas of remanufacturing, which is design for remanufacture tools and methods. This study is interested to analyse the solutions to help designer in remanufacturing activity despite the barriers stated earlier.

The topic on DfRem tools/methods deserves attention; therefore, this topic is given the focus through reviews of previous studies to describe the research status, identify the research gaps, and consequently propose possible further research directions. Structurally, there is a structure for the reviews: 1) history and some background of DfRem tool/method; 2) the concept of tools/methods in this dissertation and presentation of previous studies from general and specific formats; 3) discussion on DfRem tools/methods classification; and management; and 4) conclusion and the first research question that will be treated in the proposition chapter.

2.5.1. History and Background

For a better understanding, the definition of design for remanufacture is repeated in this section for ease of referencing. Synthesized from several definitions, it is a product and process design that facilitates steps involved in remanufacture using design aids. The design aids exist in the form of tools, methods, and approaches. Even though there has been not much evidence showing the exact year and the form of the first design aid for remanufacturing, several significant studies had been recorded as early as 1993 on the

remanufacture structure matrix by Shu and flowers. According to Amezcuita et al. (1995), the formalized general design guideline for remanufacturing and recycling is found in German engineering standard, VDI 2243 in 1993. It was then followed by significant studies from Amezcuita et al. (1995), Bras and Hammond (1996), Shu and Flowers (1999), and Sundin (2004) on the early design aids that focused on defining product's characteristics in facilitating remanufacturing from the aspect of economic and general remanufacturing process (disassembly, cleaning, recovery, reassembly, and inspection process).

With the advancement of technology, these design aids evolve in various angles which make this topic richer and more interesting to be analysed. A wider perspective of remanufacturing has been taken into consideration in developing DfRem's tools and methods such as considering environmental factor (Tchercthian et al., 2013; Wu & Kimura, 2007) and reverse supply chain aspect (Kizilboga et al., 2012). Hatcher et al. (2011) viewed this change of trend over time in quantity versus quality perspective. They stated that the earlier design aids only focused on quantitative solution, while the recent research has the tendency to improve the design process qualitatively. This phenomenon could be due to the belief that DfRem should be implemented early in the design process where less technical data is available (Amezcuita et al., 1995; Zwolinski et al., 2006). However, with the same concern, this reasoning contradicted with the argument made by Amezcuita et al. (1995) in their future work section. They emphasized on the need of quantitative solution to help designers to measure remanufacturability and give selection on the different concepts in enhancing remanufacturability. All in all, due to the fact that this topic was only published in previous studies from as early as 20 years ago, it is still difficult to indicate any clear changes in the trend over time (Hatcher et al., 2011).

2.5.2. DfRem Tool/Method as Formalized Expertise

In this dissertation, DfRem tool/method is seen as a formalized expertise with the assumption that one tool/method contains an expertise of one studied area. Taking this statement into consideration, the existing tools/methods indirectly built-up a pile of integrated remanufacturing knowledge-base that contains solutions to optimize remanufacturing activity. Furthermore, through the required tools/method's inputs, this so-called remanufacturing knowledge-based provides an upstream action that could be taken by designer/remanufacturer. For example, in order to use a DfRem tool/method, the user

must prepare several information in advance. The results from the early manipulation/simulation could also allow users to discover the crucial variables that impact the overall process. These are some of the upstream actions that might help designer/remanufacturer to plan a better remanufacturing activity ahead.

2.5.3. General and Specific DfRem Tools/Methods

When discussing this topic, we cannot avoid from emphasizing the difference between general and specific DfRem tools/methods.

i. General DfRem Tools/Methods

General design approaches exist for quite some time, and they have the advantage for their familiarity (Hatcher et al., 2011). In addition, the fact that this type of tool/method is widely used by the industry has also made the integration of dfRem easier. In an ERN workshop organized by our laboratory in March 2016, a participant asked a question about the used/known tools for remanufacturing. There were several answers on some of the general tools/methods by other participants in response to the question such as Life cycle Assessment (LCA), Life cycle Cost analysis (LCCA), Social Life cycle Assessment (SLCA), Bill of Material (BOM), and Material Flow Analysis (MFA). In the context of operational and optimization, LCA, LCCA, and SLCA are the common lifecycle tools that can be applied in remanufacturing to estimate and assess the environmental impact (LCA), cumulative costs (LCCA), and social impact (SLCA). Besides that, BOM might help in the disassembly and reassembly process, and MFA aids in material decision making as it tracks material flow.

Other than the above commercial general tools, Hatcher et al. (2011) had listed some of the general design concepts used to enhance dfRem process. Some of them are studies by Kimura et al. (2001) and Halstenberg et al. (2015) that used modularisation method to boost disassemblability, recoverability, and upgradability of remanufactured product. Sherwood and Shu (2000), and Mok et al. (2015) on the other hand applied Failure Mode Effect Analysis (FMEA) method to reduce remanufacturing waste. Yuksel (2010) adopted Quality function deployment (QFD) concept that may help transform remanufacturing needs into engineering characteristics and prioritize those characteristics.

Even though these general approaches seem as if they are easier to understand and use, the fact that they have not been developed for remanufacturing purposes makes them incomprehensive assistance in improving remanufacturability, and some of them did not

provide any guidelines on how DfRem can practically carried out (Hatcher et al., 2011). Therefore, this dissertation will concentrate on the specific DfRem tools/methods as the research area.

ii. Specific DfRem Tools/Methods

Specific DfRem tools/methods refer to tools/methods that are specifically built to facilitate remanufacturing activity in considering remanufacturing information and characteristics during the creation phase. With this definition, tools/methods might exist in many forms that vary such as static reference format in providing useful information and knowledge for designers/remanufacturers, and software and calculation format that users can manipulate and simulate for optimum results. Most of the DfRem aids are in form of calculation models that could be used for quantitative analysis and outputs. In this form, the possibility to transform the end results into application software tools is high, which has been the prominent “future work” for the calculation tools/methods studies. Ilgin and Gupta (2012) gathered and presented the basic information of mathematical models and analysis of remanufacturing systems. They discussed the basic mathematical and engineering concepts such as the following:

- Taguchi loss functions
- Analytical hierarchy process
- TOPSIS
- Goal programming
- Fuzzy logic
- Linear physical programming
- House of quality
- Line balancing techniques
- Simulation
- Experimental design and orthogonal arrays
- Maynard operations sequence technique
- Linear integer programming
- Queuing theory
- Genetic algorithms

Static references function as a guideline for designer and remanufacturer to practice better remanufacturing activities. Sundin (2004) has developed The RemPro Matrix which has been among the earliest reference tools for remanufacturing, that guide designer in product properties issues related to remanufacturing step (inspection, cleaning, disassembly, storage, reassembly, and testing). In 2007, Ijomah et al. (2007a, 2007b) have developed DfRem guidelines that listed some important requirements on remanufactured product/design characteristics from material, assembly technique, and product structure perspectives. Since cleaning process is among the most demanding steps in remanufacturing process (Liu et al., 2013), Liu et al. (2013) established a reference on the principles of remanufacturing cleaning methods selection. This principle considers cleaning objects, core contamination, cleaning force, and cleaning medium.

DfRem metrics is another type of tool/method to assess remanufacturability of a component/product design which allows the design team and decision-makers to gain insights of the product design as well as the different aspects of product remanufacturability in the early design stage. DfRem metrics evaluates remanufacturability by transforming product features into appropriate mathematical equation by using mathematical operations and weighting concept. An early study by Bras and Hammond (1996) introduced metrics for assembly and disassembly, testing and inspection, cleaning, part refurbishing, and part replacement. These metrics are then combined into a remanufacturing index for a single total outcome. Fang et al. (2014) introduced DfRem metrics based on design information in CAD models, for example, bill of material, assembly and mating features, dimensional and tolerance features. Disassembly complexity metric, fastener accessibility metric, disassemblability metric and recoverability metric are developed to evaluate the feasibility of a product or a component that will be remanufactured based on the product design information (e.g., CAD model).

In 2013, Seifert et al. had created reCORE (research for efficient Configurations Of Remanufacturing Enterprises) with the aim to manage high variety and complexity issues in production organization, production planning and control, identification technologies, and core management in remanufacturing. Shu and Flowers (1999) had created a tool to help designer in choosing a proper fastening and joining methods from the economic perspective by considering the cost of manufacture, assembly, maintenance, remanufacture, and recycling. Kizilboga et al. (2013) have developed Remanufacturing Network Design Modelling

(RNDM) to determine optimal geographical locations of remanufacturing centres by considering economic and environmental impact. When it comes to measuring environmental impact for the remanufactured product, we have CLOEE (Gehin, 2007), a tool that allows designer to easily test many closed loop strategies (reuse, recycle, remanufacturing) by using bricks concept. Ismail et al. (2014) had created a beta-version simulation tool to quantify the environmental burdens of remanufacturing operation. Golinska-Dawson and Pawlewski (2015a, 2015b) worked on tools to assess economic, environmental, and social indicators in remanufacturing process.

There are several researchers that have reviewed remanufacturing tools/methods in a specific study area. For example, Goodall et al. (2014) had listed 41 remanufacturing decision making tools in their review including REPRO2 (Gehin et al., 2008), PLETS (Dunmade, 2004), ELDA (Chen & Wu, 2003), RDMF (Subramanian et al., 2013). Besides that, Fegade et al. (2015) had listed 10 DfRem tools and methods including MGE (Tchertchian et al., 2013), ELSEM (Remery et al., 2012), PURE (Xing et al., 2007).

2.5.4. Tools'/Methods' Classification

i. The Importance of Management and Classification

The previous literature reviews on DfRem tools/methods have shown that each tool/method functioned in a specific stage with specific inputs in order to achieve specific objective/s as the output. One of the problems that have been highlighted previously is the scarcity of these tools/methods being used by the industry. Considering the numbers and various characteristics of DfRem tools/methods, it may be due to the lack of effort in classifying and managing them in order to allow efficient usage. Pretending that remanufacturing tools/methods can be used as valuable academic resources, it is important to manage and classify the resources in order to allow an adequate retrieval process.

In addition, classification helps describe, organise, and control tools/methods information. It creates order in understanding what are the responsibilities of a sector (read as remanufacturing activity) and how it operates, and enhances the capacity to share information and knowledge. In this dissertation, classification is explained for the purpose of managing records and other business information according to business context within an organisation. The Australian Standard for Records Management, AS ISO 15489 (2001), defines classification as the: systematic identification and arrangement of business activities

and/or records into categories according to logically structured conventions, methods, and procedural rules represented in a classification system. It controls the vocabulary used, which generates consistency in the description of information produced by business activities and improves retrieval of that information. The capabilities of classification tools for records management can be extended to assist sentencing and disposal. Imposing a classification system can also mitigate some organisational risks.

ii. The Existing Classification Methods for DfRem Tools/Methods

There are several efforts in classifying dfRem tools/methods to facilitate reviews and to enhance understanding. The existing reviews emphasized on the following forms of classification:

- Type of tools/methods in terms of specification: General or specific DfRem tool (Hatcher et al., 2011); analytical, guiding, or information tools (Hernandez Pardo et al., 2011).
- Type of data analysis: Quantity (Ilgin & Gupta, 2012) or quality analysis/output (Hatcher et al., 2011).
- Tool's function: Product design, reverse and closed-loop supply chain design, selection of used products or evaluation of remanufacturing facilities (Ilgin & Gupta, 2012); decision-making tools or optimization tools (Goodall et al., 2014).
- Usage stages: Strategic, tactical, or operational (Goodall et al., 2014); design, planning, or process (Ilgin and Gupta, 2012).
- Tool's/method's format: Software, reference, conceptual, or calculations (Hatcher et al., 2011).
- Tool's/method's capacity: High, medium, or low level (Hernandez Pardo et al., 2011).
- Decision factors: Economic, environmental, social (Goodall et al., 2014).

In a comprehensive literature review of design for remanufacture by Hatcher et al. (2011), the issue on design aid was highlighted in one of the subtopics as one of research trend. The authors separated design approach into two categories: 1) design aids that are specifically built for remanufacture; and 2) the use of existing design approach concepts that are relevant for remanufacture. Besides classifying the type of data analysis into qualitative and quantitative, the authors also categorized them into several forms of format, which can be defined such as the following:

- Application software: Tool/method that existed with the interface that can be executed by users to perform a function.
- Reference: Tool/method that existed as a reference, principle or guideline that may help user to assess remanufacturability, do the decision making and prioritize actions
- Conceptual: Modelling tools that usually utilise diagramming approaches to capture specific concepts, to separate these concepts logically, and to represent relationships between the concepts.
- Calculation: Tool/method that existed in formula form or mathematical model

Ilgin and Gupta (2012) in their book reviewed remanufacturing from quantitative modelling and analysis. They then divide those modelling and analysis into three main categories which are design issues, planning issues and processing issues. From the book, these categories described as following:

- Design issues: Issues that involve long-term decisions (years) and related in defining the structure of remanufacturing system.
- Planning issues: Issues that involve medium-term decisions (3 months to 1 year) and determine the flexibility and performance of a remanufacturing system.
- Process issues: Issues that involve short-term decisions (minutes, hours, or day) and determine the operational effectiveness of a remanufacturing system.

Under every category, the authors listed several sub issues. For design issues, there are product design, reverse and closed-loop supply chain design, selection of used products, and evaluation of remanufacturing facilities issues (Figure 16). However, the “design” notion (with the integration of time in the above description) seems a bit confusing from the DfRem definitions that have been discussed earlier. If we refer to the DfRem goal stated by Hatcher et al. (2011), which is “to enhance remanufacturability”, we may as well include the planning and process issues in the DfRem components.

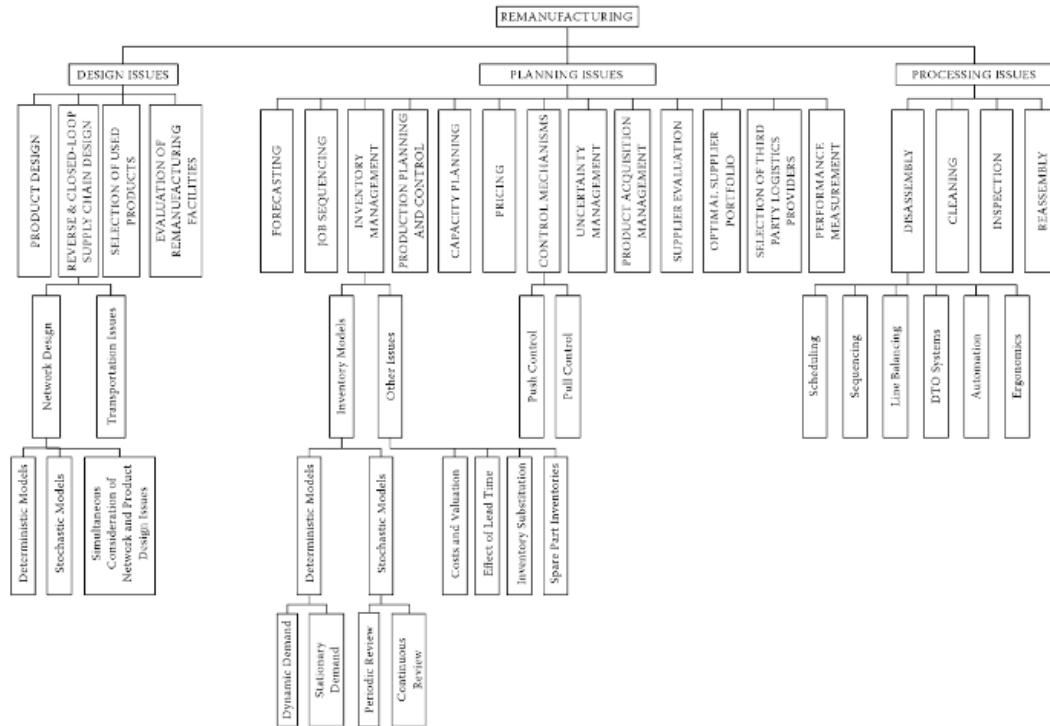


Figure 16: Classification of issues in remanufacturing (Ilgin and Gupta, 2012)

On the other hand, Goodall et al. (2014) reviewed the tools and techniques used to assess remanufacturing feasibility by focusing on the decision-making process where the key subject is to determine whether to conduct remanufacture or not. They classified remanufacturing decision stages into three categories: strategic, tactical, and operational (Figure 17), and addressed the three pillars of sustainable development (economic, social, and environmental) as remanufacturing decision factors.

- Strategic decision stage and tools: It is a high level decision making, and it aimed to shape the long term future of a business. In remanufacturing context, this stage is usually taken to review whether remanufacturing is giving the desired effect on the business. Strategic tools have been designed to assist decision makers in assessing remanufacturability feasibility at a strategic level. These tools evaluate product suitability, business suitability, and internal suitability for remanufacture (Goodall et al., 2014).
- Tactical decision stage and tools: It tends to focus towards the medium term with the aim of providing a method in implementing the chosen strategy. Tactical tools aim to evaluate a particular product design to determine appropriate end of life strategies

for individual components. The main difference between these tools and the operational tools is the negligence for the Middle of Life effects (i.e., the condition of the returned product). The main use of these tools is to evaluate the best practice for remanufacturing facilities at the end of life stage and product designs stage (Goodall et al., 2014).

- Operational decision stage and tools: This stage is encountered on a daily basis. The aim is to assess individual products'/components' remanufacturability and remanufacturing facility through product inspections where the products are filtered. Operational tools are used to evaluate a specific product instance for remanufacture such as during inspection phase (Goodall et al., 2014).

From the reviews of literature, there are other types of tools/methods such as optimisation tools/methods that have not yet been analysed. The optimization tools' goal is to maximize one or more parameters while keeping the others within their constraint. The most common goals include minimizing the cost and maximizing the output and efficiency through equipment, operating procedure, and control optimization.

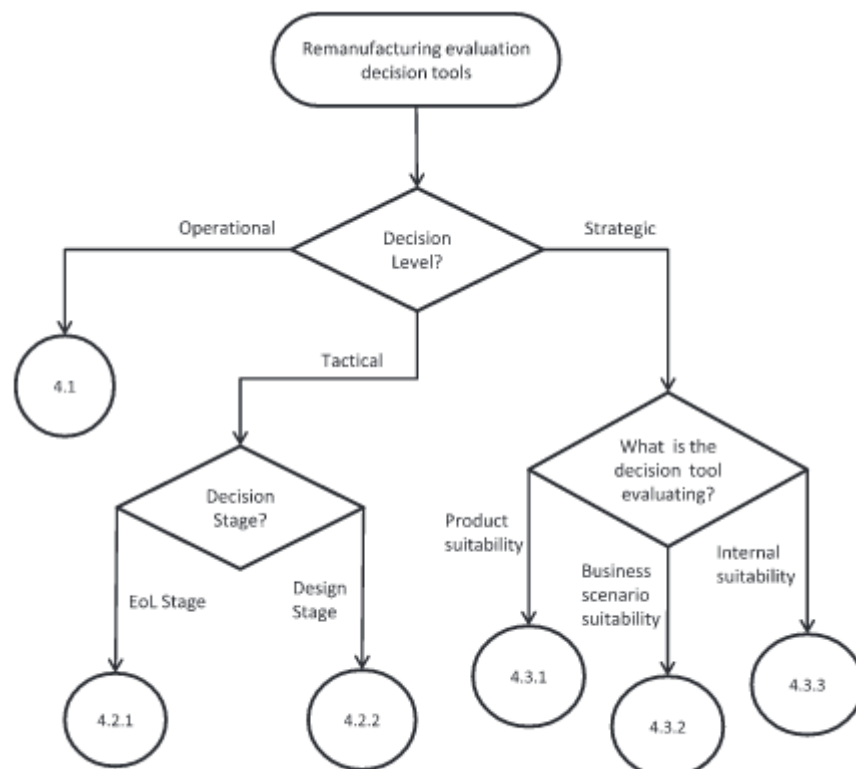


Fig. 5. Process for categorising tools based upon functionality.

Figure 17: Process for categorising tools upon functionality in decision making stages (Goodall et al., 2014)

Other than remanufacturing knowledge area, Hernandez Pardo et al. (2011) have explored on the classification of eco-design projects and eco-tools in the classifying and characterizing work. After exploiting over 40 case studies, the authors come out with three classification criteria which are tool's complexity, type of tool, and tool's main function. Tool's complexity criterion is related to the resources required in using the tool, which are amount of time, amount of input information, and level of expertise required. There are three levels of complexities:

- High level of complexity: Tools that need a high level of information, more time to be operated, and need to be operated by experts. Purely quantitative output need to be interpreted by experts. Example: LCA software.
- Medium level of complexity: Simpler to use than those of high level of complexity. Need less information and time to produce results. Output data can be qualitative and quantitative, rough but accurate assumption to provide discrimination. Examples: LCI tools, LCC software.
- Low level of complexity: Quick and easy-to-use tools. They do not require previous knowledge of their use. They are very useful for a quick environmental product profiles with not many details. Examples: Eco-design wheels, databases, and design frameworks.

For the type of tool/method, Hernandez Pardo et al. (2011) proposed three categories, namely analytical, guiding, and information tools. The following are the elaboration:

- Analytical tools: Tools oriented to carry out systematic analyses with a high level of detail. The outputs of these tools mostly are quantitative. Examples: LCA, LCI, eco-indicator.
- Guiding tools: Tools oriented to provide guidance to the user to produce simplified environmental product profiles. They are used to support idea generation and advise the designer. Examples: eco-design pilot, guidelines, strategic wheels.
- Information tools: Tools developed to provide general information about materials, substances, and low levels of detail frameworks. In addition, the information is very accurate. It is often used in just one stage of product design process. Examples: databases, checklists, design for manufacturing/recycling/assembly.

The third classification is tool's main function which focuses on the practical utility of the tools specifically on the principle function (if there is more than one function). Besides that, the secondary usages are also included in the database for designer's references.

2.5.5. Conclusion and Research Question 2

Research in remanufacturing progresses hugely as there are many studies done on DfRem tools/methods in academic realm, which make it become one of the DfRem research trend. During this research, the existence of DfRem tools and methods is easily remarked as one of the solutions in helping designer to create remanufacturable products. The previous literature reviews on DfRem tools/methods have shown that each tool/method functions in a specific stage with specific inputs in order to achieve specific objective/s as the output. The use of these tools/methods is seen as a further step after designer knows the character that he/she wants to achieve, which is discussed in the first research question. Ideally, this trend will contribute to a more effective and optimal design/redesign process, replacing the older one that without any/less design aids. However, DfRem tools/methods have been hardly used by the industry (Hatcher et al., 2011). This may due to many reasons and one of them is poor information management such as lack of tools/methods classification, tools/methods databases, and tools/methods reviews. Due to the disadvantages, designer and remanufacturer might consume a huge time and effort to search, analyse, and choose appropriate DfRem tools/methods. Consequently, the second research question is **“how to help designer to choose the existing DfRem tools/methods to design remanufactured product for sustainable development?”**

So, the second proposition in chapter 4 will focus on managing and classifying the operational DfRem tools/methods. The operational DfRem tools/methods can be described as tools/methods that are used by designer after making the decision whether to remanufacture a product or not that is taken by senior/upper management. The framework and definition of remanufactured product for sustainable development defined in the chapter 3 will be used to put in place this second proposition. The results are expected to portray an overview of the existing operational DfRem tools/methods for facilitate their usage.

2.6. Conclusion and Work Positioning

Besides giving a deeper understanding on this topic, the literature reviews on remanufacturing and DfRem tools and methods permit the demonstration of various functions of DfRem tool/method in order to overcome remanufacturing barriers. For every outcome of DfRem tool/method, it requires a profound research in one remanufacturing area as an essential part of every study. The research findings as well as research results (in this context: DfRem tool/method) are important contributions to enrich the knowledge. They can also be considered as a milestone in every remanufacturing area. For this reason, this study viewed each remanufacturing tool/method as a formalize expertise where one tool/method represents one expertise. This formalize expertise is very useful to plan remanufacturing in advance, which is the design stage. Ideally, if a designer or remanufacturer applies the existing DfRem tool/method in the early stages of remanufacturing activity, some problems might be encountered and resolved in advance. Unfortunately, as stated earlier, these tools/methods are seldom used by the industry, and this issue needs to be taken seriously. Therefore, this study viewed this problem as a significant research gap. In addition, this dissertation aimed to bridge this gap by proposing a methodology to facilitate designer in selecting and applying the existing tools/methods in the early design stage.

One of the previous research questions intended to resolve a more general problem, which is “how to help designer to design remanufactured product for sustainable development?” This general question is a significant problem faced by European companies in accordance to European industry requirements including a resource-efficient manufacturing and support on circular economy. This piece of work also aimed to facilitate remanufacturing knowledge transfer as much as possible.

The first research question is focused on the working framework, definition, and characterizing remanufactured product for sustainable development. Whereas the second research question is intended to discuss the DfRem tools/methods and how to enhance the usage of those tools/methods from classification and management aspects. The overall view of this dissertation is presented in Figure 18.

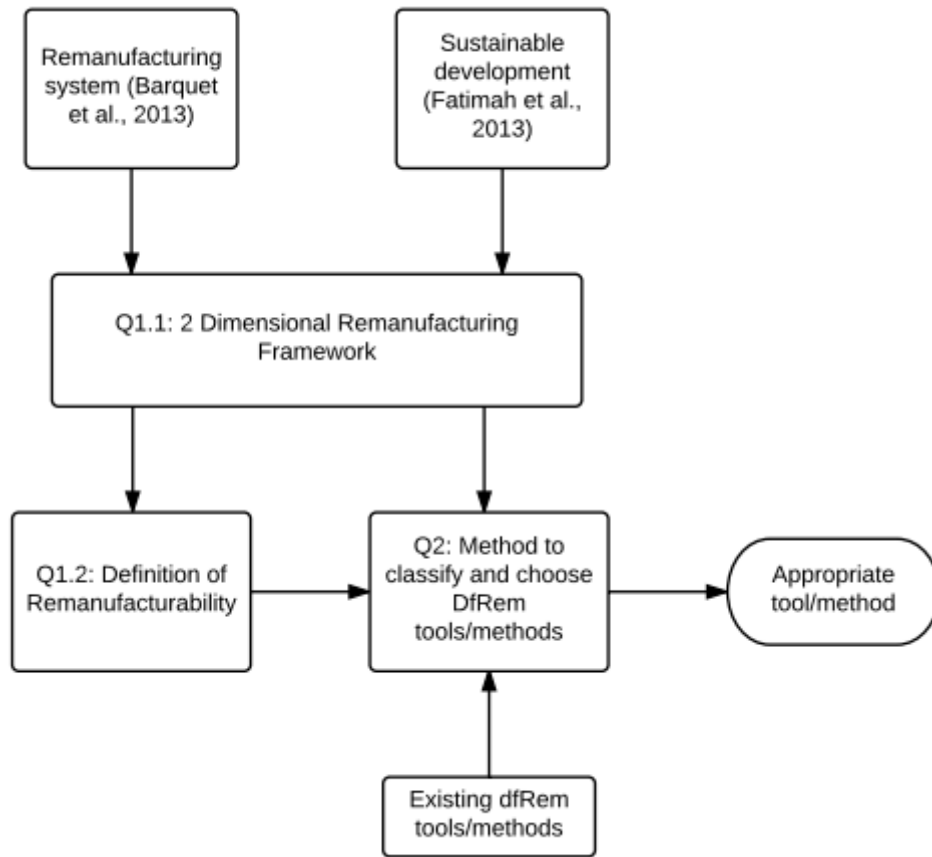


Figure 18: Overall View of Research Work

Chapter 3 (Proposition 1): Two-dimensional Framework of Remanufacturing (2DFR) and Definition of Remanufacturability

3.1. Research Methods for Proposition 1

From the elaborated frameworks and their elements in the previous chapter, we can see the importance of having a structured and inclusive framework in planning and directing remanufacturing activity. The missing of one of the frameworks might affect the decision making process. Previous studies have revealed that remanufacturing from a single perspective was insufficient and need to be upgraded. Therefore, the first proposition of this dissertation deals with:

- Designing an integrated framework by considering the sustainable development pillar and remanufacturing system.
- Defining and characterising remanufacturing feasibility from the both mentioned aspects.

Based on the problem statement and research question in the previous chapter, our research flow-cum-research method was as follows:

- a. An extensive literature review was conducted to gain a basic knowledge, positioning research, and providing context within the following main areas:
 - i. Remanufacturing operation
 - ii. Design for remanufacturing
 - iii. Sustainable development

Other than using them as the keywords in this research, these areas have been kept in mind when attending conferences, meeting other researchers, and visiting companies.

- b. Chose a remanufacturing framework by conducting content analysis of the existing literature. The following two aspects had captured our attention:
 - i. Sustainable development as the decisive factors.
 - ii. Remanufacturing system as components of the entire remanufacturing activities.
- c. Developed the new remanufacturing framework as a proposition in a way that it can also be applied practically.

- d. Defined every element in the developed framework that generates a new definition of remanufacturability.
- e. Validated the developed framework by conducting a workshop among designers and remanufacturers. During the workshop, participants were requested to work on the framework and answer some questions. Their responses and feedbacks were gathered and analysed.

3.2. Two-dimensional Framework of Remanufacturing (2DFR)

From the above descriptions, the construction of a two-dimensional framework of remanufacturing (2DFR) aimed to integrate the two perspectives which were sustainable development proposed by Fatimah et al. (2013) and remanufacturing system proposed by Barquet et al. (2013) into one. To make the analysing and interpreting process easier, we have created a system that fixed elements with numbers and alphabets. Starting with the elements of sustainable development as below:

- 1 for economic aspect
- 2 for environmental aspect
- 3 for social aspect
- 4 for technical aspect

Followed by the elements of remanufacturing system as below:

- a for design for remanufacturing
- b for reverse supply chain
- c for information flow in remanufacturing system
- d for employees' knowledge and skills
- e for remanufacturing operation
- f for commercialization of remanufactured product

The integrated view has been achieved with the help of framework table. The framework table was constructed in "4x6 table" where the four elements of sustainable development were arranged in rows and the six elements of remanufacturing system were arranged in columns (See Table 2). For example, 1 (a) cell represented both elements of design for remanufacturing and economic perspectives such as product material's cost. The concept of pairing two elements together was applicable for the other cells. The table can be

analysed vertically to know the characteristics of each element of a remanufacturing system from sustainable development perspectives. Oppositely, the table can also be analysed horizontally to know the characteristics of each element of sustainable development from a remanufacturing system perspective. Both ways of analysis can be used depending on the context of discussion.

	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufactured product
1. Economic	1a	1b	1c	1d	1e	1f
2. Environment	2a	2b	2c	2d	2e	2f
3. Social	3a	3b	3c	3d	3e	3f
4. Technical	4a	4b	4c	4d	4e	4f

Table 2: 4x6 Table

3.3. Remanufacturability from 2DFR Perspectives.

The word remanufacturability was introduced in 1995 by Amezcua et al. (Xing, 2013). At that time, the definition of remanufacturability was not given by the authors, but they suggested that enhancing remanufacturability should be carried out in the early phase of the design process. It was in 2005, Debo et al. stated that each component had a certain ability to be remanufactured and could be called as remanufacturability. Jin (2008) defined remanufacturability as “the fraction of used products that can be remanufactured”, while Wu (2012) defined remanufacturability as an attribute of a product which was used to describe the product’s possibility and ability to be remanufactured.

From the given definitions, the word remanufacturability was used in this dissertation to represent the design requirements for a product to be remanufactured.

These remanufacturing requirements were expected to be implemented in a new product to increase its possibility to be remanufactured. The previous two-dimensional thinking concept had generated a new approach in viewing remanufacturability. Even though the content was similar to what we had described earlier, the integrated description of every cell was needed to facilitate the designer in using it. Therefore, this section aimed to characterise remanufacturing requirement that can also be seen as remanufacturabilities from both perspectives represented in every cell in the proposed table of 2DFR.

The characterisation tables (See Table 3, 4, 5, 6) applied the concept of horizontal analysis where the elements of remanufacturing system were regrouped for each element of sustainable development. Each cell contained remanufacturing requirements found on the scientific literatures, remanufacturer's websites and from author's own opinion. In the last column, the provided lists consist of:

- a) factors that influence remanufacturing requirements
- b) the possible implementations in order to achieve those requirements as an early general idea

This table was very useful as a guideline and checklist for designers and remanufacturers in designing remanufactured product/process for sustainable development. The description of every element was elaborated in the following section, and remanufacturability tables (table 3, 4, 5, and 6) with references are available in annex A.

3.3.1. Remanufacturability from Economic Perspective

In this section, the description of every characteristic that might increase the remanufacturability from an economic perspective listed in Table 3 was defined. In general, the objective of every business is to have maximum profits and minimum cost and the same goes for remanufacturing. Even though economics had become the major motivation to remanufacture (Hatcher et al., 2011), its long cycle and many uncertainties might result in contrary. Therefore, giving a sufficient attention on every factor that might influence the remanufacturing's profit and cost was important to ensure its sustainability from an economic perspective. More detailed explanations for every component in the remanufacturing system were as follows:

i. Economic + Design for Remanufacturing

From an economic point of view, designing a product or component with characteristics that can assure a high profit during remanufacturing activity would increase the product's remanufacturability. For a general rule, any design that can reduce operating time could increase the profit since in business, time equals to money. Simple form and minimum number of fasteners were some basic guidelines that the designer can applied whenever possible. For economies of scale benefits, Shu and Flower (1993) suggested that a mass-produced item because it was more likely to provide enough components for remanufacturing operation. From a material prospect, choosing a material type that can be recuperated optimally at the end of its life for remanufacturing was also essential (Lopez Ontiveros, 2004).

ii. Economic + Reverse Supply Chain

From a product point of view, economic profit might come from the product's characteristic that can reduce the costs of transport, packaging, and storage by having a product that was lighter in weight and in "easy-storage" form (Ferrer & Clay Whybark, 2000). Meanwhile, from a remanufacturing process perspective; inexpensive fuel type, optimum lot size, transport type and capacity, and trajectory planning would help to reduce the transport cost. Durable packaging and storage system might reduce the product damage, while a standard, flexible, and reusable packaging and storage system could reduce the packaging and storage cost (Ferrer & Clay Whybark, 2000). In terms of duration, a short reverse supply chain channel might reduce the cost (Barquet et al., 2013). High quantity of return and good balance between return rates and demand rates would also increase the profit. Having said these issues, type of return contract and collection system of used-products were the key-elements to be considered. Xerox for example, is a global leader in the remanufacturing of photocopiers whose return is secured by lease sales (Amezquita et al.,1995).

From a wider perspective, planning the appropriate remanufacturing centre's location and capacity function of used-product suppliers could optimise the reverse supply chain time and cost (Subramoniam et al, 2009; Kizilboga et al., 2013). In addition, choosing a beneficial relationship between supplier and remanufacturer from the seven types of relationship proposed by Ostlin (2008) can also be considered.

The ability to pre-assess the remanufacturability of used products at the customer's place before being transferred to the remanufacturing company can also help to separate the valuable and less-valuable components at the early stage of a reverse logistics system. Product characteristic that allowed the operator to easily detect its failure condition may also help to ease the remanufacturing process. This can avoid the unnecessary transportation and encourage local recycle activity which could reduce the cost and energy (Ferrer & Clay Whybark, 2000; Barquet et al., 2013).

iii. Economic + Information Flow in Remanufacturing System

An information flow connects a remanufacturing product and process elements. Applying a low-cost but sufficient information flow system is necessary to avoid any unnecessary loss. Mastering the characteristic of remanufacturing activity might help to determine the appropriate information flow system. Externally, Barquet et al. (2013) and Lindkvist and Sundin (2013) suggested that companies should collaborate with remanufacturing stakeholders and established communication throughout the remanufacturing process to reduce the cost.

From an economic perspective, information flow played an important role in dealing with remanufacturing uncertainties (Barquet et al., 2013). An effective information flow management allows a good analysis and forecasting which can decrease the uncertainties and increase the business profit.

iv. Economic + Employee's Knowledge and Skills

Whether in product or process sector, reducing the employment of experienced or skilled employee in order to reduce the cost still cannot ensure an augmentation in the total profit. Investing in skilled workers may sometimes boost the production. However, limiting the skilled workers' employment just for the crucial task might be an option. Otherwise, employees can always be trained by the company itself (Barquet et al., 2013). Providing training and information to employees are always a good investment for the company (Ferrer & Clay Whybark, 2000; Liu et al., 2013; Barquet et al., 2013, Jacobsson, 2000). Jacobsson (2000) proposed that employees should be trained to handle the variable and uncertain quality and quantity of cores as their conditions were difficult to predict. Another factor that determines employee's characteristic was the location of remanufacturing

centre. Different location would offer different employee in terms of quantity, skill level, and salary rate.

v. Economic + Remanufacturing Operation

For economic feasibility, a remanufacturing operation cost should be less than a new product cost, unless the cost of disposal was high enough to justify the expensive remanufacturing process (Shu and Flower, 1993; Lopez Ontiveros, 2004). According to Atasu et al. (2010), the larger the differential (between the remanufacturing cost and the new product cost), the more attractive it becomes.

Previous research has shown that parts replacement and cleaning operations had become the most expensive operations among others (Hammond et al., 1998; Gamage et al., 2013). Furthermore, Gamage et al. (2013) in their study has proven that four out of seven factors that raised the cleaning cost was due to physical characteristics of the product and/or process which makes the cleaning process more complex. Therefore, by considering more aspects of the costly operations during the product design stage may reduce the remanufacturing operation cost.

vi. Economic + Commercialization of remanufactured product

From an economic perspective, to ensure the profit of remanufactured product sales, remanufactured product price must be less than the price of the new ones (Lopez Ontiveros, 2004). The redemption price of used product must also be less than remanufactured product price (Lopez Ontiveros, 2004). In many firms, manufacturing/sales and remanufacturing/remarketing operations were carried out in different divisions to facilitate management. However, from quantity decisions perspective, these two divisions were linked together since the sales of new products will determine the supply of remanufactured ones in the future (Toktay & Wei, 2011). Therefore, managing the transfer pricing issue that existed between the two divisions might define the optimal prices for the two products.

Another popular issue concerning commercialisation was cannibalisation. Many believed that cannibalisation may hinder company's profits. Conducting marketing studies, identifying correct price points (Atasu et al., 2010), selling through different channels (Guide et al., 2002), remanufacturing was only a subset of their product line where they believed cannibalisation effects were limited (Valenta, 2004), selling the new and remanufactured products to different market segments (a different geographic region, or when the

customers in these segments had distinct preferences) (Toktay and Wei, 2011) can limit the cannibalisation.

The Kodak’s single use camera was an example of perfect substitution, where the “container” parts were being reused multiple times with a readily agree consumers. Applying “perfect substitution” whenever possible was an excellent condition to remanufacture. Another factor that increased remanufacturing activity was government subsidies. Webster and Mitra (2007) suggested that the policy maker to divide the policy inputs between manufacturers and remanufacturers to achieve an optimal result from this aid.

From a customer point of view, assuring an affordable price for remanufactured product may increase demand and encourage remanufacturing activity. The definition of “affordable” was different depending on the market segments. Studies on consumer’s willing-to-pay were essential besides other studies on marketing. Identifying a correct price point may avoid a too-high price (that can lead to customer declination), or a too-low price (which may generate the unnecessary suspicious and insecurity).

4 Pillars SD	6 Aspects of Rem System	Characteristics	Implementation (Product or Process)
Economic	Design for reman (product)	Minimum operating time	Product form, type, and number of fastener, material, production type, product's cost
		Mass-production	
		High (critical) material recovery	
		Less material/component used	
		Minimum cost	
	Reverse supply chain	Minimum transport cost	Product/packaging/storage characteristic, optimum lot size, stock size, transport type/capacity/cost , type of fuel, customer demand, machine capacity, trajectory planning, centre locations cost and capacities, relationship between supplier and remanufacturer, merge with direct supply chain, buy back cost, return and demand rates, distance, Product features, pre-assess activity, Labor Management and Workforce Flexibility,Proactive Transportation Management, Secondary Market Strategies, Consumer and Market Engagement
		Minimum storage cost,	
		Minimum packaging cost	
		Short RSC channel	
		Efficient & beneficial collection system	
		High return rates and demand rates	
	Possible to pre-assess		
Information flow in	Minimum cost	Tracking method/device, collaboration,	

	reman system	Reduce uncertainty in the timing and quantity of returns and demand	communication, Material flow, return and demands rate, forecasting
	Employee knowledge and skill	Maximum profit,	Number and type of employee, employee's salary, location, training and formation
		Minimum cost,	
		long-term investment on employee	
	Reman operation	Process cost < new product cost	Product characteristic, lean remanufacturing process (energy, time), remanufacturing cost, type and amount of consumption, lot size
	Commercialization reman product	Remanufactured product price < new product price,	Product price, market demand, government policy, transfer pricing, direct competitors, maximize market share of remanufactured product, market studies, Market segment
		Redemption Price < remanufactured product price,	
		High demand, minimum cannibalization	
		Price that convinced customers	
		Systematic	
Effective			

Table 3: Remanufacturabilites from economic perspective

3.3.2. Remanufacturability from Environmental Perspective

This section elaborated remanufacturing characteristics from an environmental perspective. In general, environmental characteristics aimed to have a low environmental impact in the overall remanufacturing activity. For this reason, life-cycle thinking was necessary in operating all stages of remanufacturing activity to avoid any environmental impact transfer.

i. Environmental + Design for Remanufacturing

To increase remanufacturability from environmental and design perspective, product and process should possess high environmental profit. Many previous researches on Design for Environmental highlighted the generic design guidelines that can be applied to remanufacturing design for environmental profit whenever possible. Some major guidelines were as follows:

- Chose material, machining methods, and product design that can minimise energy and resource consumption in the production phase (Lopez Ontiveros, 2004; Luttrupp & Lagerstedt, 2006).
- Chose material that can be easily recovered during the remanufacturing process (Lopez Ontiveros, 2004).
- Used structural features and high quality materials to minimise weight given such choices did not interfere with other functional priorities (Luttrupp & Lagerstedt, 2006).
- Chose a design solution that can minimise energy and resource consumption in the usage phase for a product that had a significant impact due to the consumption in the usage phase (Luttrupp & Lagerstedt, 2006).

It is always important to note that not all products can gain environmental profit through remanufacturing. Therefore, conducting a pre-environmental analysis is essential to avoid unnecessary lost.

The designer must also ensure that the products were environmentally safe to be used and remanufactured by avoiding toxic substances material. Environmental legislation has made the non-toxic substitutes largely available in the current market. Replacing them with a non-toxic substitute that fulfils functional and economic requirements was an appropriate solution. Treating toxic substances with a proper treatment would be the last but the essential choice if avoiding them was not possible (Luttrupp & Lagerstedt, 2006).

ii. Environmental + Reverse Supply Chain

From a product point of view, environmental profit of reverse supply chain can be gained through product's characteristics (product's weight and form) that could minimise the environmental impact for transport, packaging, and storage system (Ferrer & Clay Whybark, 2000). Durable, flexible, and reusable packaging and storage system might also increase the environmental profit.

From the remanufacturing process prospect; optimum lot size, transport type and capacity, and trajectory planning would help to reduce environmental impact of transport. Study by Kizilboga et al. (2013) suggested an optimum remanufacturing centre's location and capacity in order to achieve the same goal.

Similar to the previous characteristic in economic + reverse supply chain, the ability to pre-assess the remanufacturability of used products at the customer's place before it was transferred to the remanufacturing company can avoid any unnecessary transportation. Companies could establish and ensure that a local recycle had planned to reduce environmental impact (Ferrer & Clay Whybark, 2000; Barquet et al., 2013). In addition, the ability to pre-assess/assess the environmental impact of a product/process was important to evaluate and reduce environmental impact from remanufacturing activities using life cycle assessment tools. The result of the assessment can be used as an environmental key performance indicator and product's/process' environmental information.

iii. Environmental + Information Flow in Remanufacturing System

Other than choosing an environmental-friendly information flow system, Barquet et al. (2013) and Lindkvist et al. (2013) suggested that companies to collaborate with remanufacturing stakeholders and establish communication and network in order to minimise environmental impact whenever possible.

iv. Environmental + Employee's Knowledge and Skills

Nowadays, even though the design department has invented many Eco-design tools to produce an environmental-friendly product, having a strong basis on the environment is always an advantage for the designer as an employee. Designer's environmental knowledge and practice would facilitate the concept of a "greener" remanufacturable product and process. Moreover, informing and educating the workers from all stages of remanufacturing operation with environmental issues would ensure a higher environmental gain at the end of the entire process. Among the solutions given were: hiring an Eco designer, sending-off designer/workers for environmental training and education, exchanging environmental knowledge and practice among the internal divisions, providing user-friendly environmental guidelines in every workstation, or simply by briefing workers with the environmental objective before the operations.

v. Environmental + Remanufacturing Operation

From a product point of view, any characteristics that help to reduce energy and resource consumption during remanufacturing operations would increase the environmental profit. Characteristics that ensure a maximum product recovery after the first usage also help to achieve the goal mentioned. Having these statements in mind while choosing the

product’s material, form, structure, component’s arrangement, surface finishing, and fastening methods, might change the designer’s perspective and decision making.

For remanufacturing operation, cleaning process has always been reported as the significant contributor for environmental impact compared to other operations (Liu et al., 2013). Well-identified cleaning purposes and technical cleanliness requirements, recognised core contaminant type and its attachment manner, acknowledged material, quantity and geometric dimensions of the cores, choosing the appropriate cleaning method, and cleaning agent were some of the guidelines highlighted by Liu et al. (2013) in order to reduce the ecological footprint. The operator can also reuse the cleaning agent whenever possible.

As for the other operations, the same method was applied as above with some adjustments to fit-in process can also be applied to achieve the same goal. Comprehensive evaluation referring to the environmental requirements can ensure degradation of the environment pollution.

Similar to the characteristic in Environmental + Design for remanufacturing, it was important to ensure that the remanufacturing operation was environmentally safe. Avoiding toxic substances in remanufacturing method and consumption might come from remanufacturer’s awareness and government’s imposition. This has led to increasing options for safer solutions for remanufacturing operations. Other than toxic substances, other issues that endangered human being were the usage of small/fine particles in remanufacturing operation (i.e. cleaning operation) and the treatment of remanufacturing residue.

vi. Environmental + Commercialization of Remanufactured Product

Customers with a sufficient environmental awareness were proven to have higher chances of buying a “greener” product, including remanufactured one (Doshanov & Ahmad, 2015). Remanufacturing benefits from the environmental perspective must be communicated in order to educate the customers. Media was detected as one of the key factors in order to achieve this goal. Emphasizing and giving a serious thought on this constraint may ensure a better future for the remanufacturing industry.

4 Pillars SD	6 Aspects Rem System	Characteristics	Implementation (Product or Process)
Environmental	Design for reman (product)	High material recovery	Material (type, mass), remanufacturing process, Product features , pre-assess activity, LCA, treating toxic substances
		High saved energy and material	
		Minimum env impact in usage	

		phase		
		No toxic substances (REACH compliance)		
		Possible to pre-assess/ assess environmental impact		
	Reverse supply chain	Minimum pollution from product and process (REACH compliance)		Product's characteristics, Energy used, stock size, type of transport, type of fuel, Centre location and capacities, distance, Product features, pre-assess activity, LCA
		high energy saving		
		Optimum centre locations and capacities		
		Possible to pre-assess/ assess environmental impact		
	Information flow in reman system	Minimum environmental impact		Tracking method/device, collaboration, communication
	Employee knowledge n skill	Well-educated and well-guided employee on environmental issue		Employees' profile, training and formation
	Reman operation	The entire reman process should result in a decrease in the total environmental impact		Lean reman operation (energy, time), surface type, material, form/shape, component arrangement, cleaning procedure, cleaning agent, lot size
		No toxic substances,		Work place, government policy, reman operation
		Respect health & environment policy		
		Possible to pre-assess/ assess environmental impact		Product features, pre-assess activity, LCA
	Commercialization reman product	Well-educate and well-guided customer on environmental issue		Media, education

Table 4: Remanufacturabilities from environmental perspective

3.3.3. Remanufacturability from Social Perspective

Remanufacturing is believed to help improve the social aspect by creating job opportunity. Other opportunities like involving local suppliers, incorporating domestic cultural features, integrating health-supporting system were some of the examples that the product developer can consider to generate a positive social impact. From a design perspective, employee's skill and motivation, customer's motivation and loyalty, quality of services and health, and safety issues should be considered and treated by designer and company's management in order to achieve social goals. In this section, the elaboration of remanufacturing characteristics from a social perspective in each element of remanufacturing system was discussed.

i. Social + Design for Remanufacturing

In most cases, a good knowledge and understanding of design for remanufacture increased the designer's capabilities to create a product with easy-future remanufacture (Ijomah et al. 2007). However, Hatcher et al. (2013) proved that designer's motivation was of greater significance. In addition to the designer's experience in remanufacturing, short formation, visiting other centres, providing remanufacturing guidelines, and brainstorming sessions might increase the designer capabilities in developing remanufacturable products.

From a product point of view, durable constraints were essential for warranty reason which signified corporate social responsibilities of an industry (Anityasari, 2008). Maintenance cost and the longevity of remanufactured products (Ferrer and Clay Whybark, 2000) had become a customer's concern when purchasing remanufactured product. Holding a definition of to be as good as new, remanufactured product must be treated to fulfil this requirement to gain customer's trust.

From a product design perspective, other than what have been described in the environmental section previously, safety issue also existed in the product's ownership matter as a product changes ownership several times over the course of its life. Grey definition between waste and what might often be patented product has been the subject of discussion at the end-of-life phase, especially for the third party remanufacturer. If a product is reclaimed and remanufactured to original design specifications with a warranty to match and resold under the same brand name, some may regard the OEM as entitled to claim the ownership and compensation for that product. If this was not the case, some may regard it as a counterfeit (APSRG and APMG, 2014). Intellectual property (IP) issue has been discussed by John and Robert (2009) with examples from real cases. John and Robert (2009) advised remanufacturers to be aware of the patent landscape of the products that they were remanufacturing and sought qualified legal consultation. As for the OEM, think about patenting your invention whenever applicable.

ii. Social + Reverse Supply Chain

In reverse supply chain operation, social aspect becomes a concern when dealing with customers or suppliers mainly in the product return after its first life cycle. From the product and process perspective, any effort that can attract users to return their product for remanufactured may easily increase remanufacturability. Attractive return program and

contract, return promotion and guideline were some of the solutions that need a profound study on customers' interest and how to balance it with a company's needs. Below are the different types of relationships between customers and remanufacturer from Ostlin (2008) that were interesting to be studied and applied accordingly:

- Ownership-based: The product is owned by the manufacturer and operated by the customer. The control of the installed base is high and it is normally regulated by contracts, as for rental, lease or product-service offer.
- Service contract: Based on a service contract between a manufacturer and a customer that includes remanufacturing.
- Direct-order: The customer returns the used product to the remanufacturer, the product is remanufactured and then the customer will get the same product back (given it is possible to perform a remanufacturing operation)
- Deposit-based: When the customers buy a remanufactured product, they are obligated to return a similar used product, thus they are also acting as a supplier to the remanufacturer. This type of relationship is common in the automotive industry.
- Credit-based: When the customer returns a used product, they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.
- Buy back: The remanufacturer simply buys the desired used products from a "supplier", which can be the end user, a scrap yard or similar, or a core dealer.
- Voluntary-based: The supplier gives the used products to the remanufacturer. The supplier can also be a customer or not.

From the remanufacturing process perspective, providing a socially safe working environment was another concern. The socially safe working environment contains healthy and safe workplace, basic human rights protection for employees, including shared benefits of economic growth, community development, and absence of discrimination (Branch, 2012). In product return issue, having a contract that protects both customer's and remanufacturer's right was another constraint to be noted. Awareness program on social responsibilities in the workplace, profound study on company's contract, and good management might increase the social safety in remanufacturing industry.

iii. Social + Information Flow in Remanufacturing System

A socially good system for an information flow aspect was defined by its ability to exchange the internal information between stakeholders within the system and to share information and data with other companies via communication and networking. Other than establishing an effective information system and management, soft skills and communication ethics played an important role in conveying accurate information and maintaining good relationship among individual or groups/departments/companies. Referring to the code of ethics for business communication, communication training and formation, and company's enforcement might overcome this constraint.

iv. Social + Employee's Knowledge and Skill

Concerning employee's knowledge and skills, the social constraint was to have employees that were capable to accomplish the given task successfully. Well-known as the labour intensive industry, remanufacturing is composed by multi-level skill tasks. Therefore, it is necessary to manage workers, according to operational and worker's profile. For certain tasks like inspection, cleaning and repair, workers with a high level of consciousness was needed (Lund, 1984). Good human resource management, training and experience would help to overcome this constraint. It has always been the employer's social responsibility to ensure the acquisition of skills and added value of their workers.

v. Social + Remanufacturing Operation

Since the worker's skill issue in remanufacturing operation has been discussed in the previous section, this section focused on the social safety, health issue, and human rights protection during the remanufacturing operation. Basically, most of the main issues have been discussed in the Section ii (Social + Reverse Supply Chain). In addition, for a high risk remanufacturing operation, company's enforcement of safety rules and regulation (OSHA) is extremely important. Experts also agreed that all workplace safety programmes should incorporate housekeeping and every worker should play a part in this matter. They should be extra alert on hazardous materials, combustible dust and other flammables, and take precaution to prevent any slips, trips and falls. This might reduce the risk of injuries and illness to employees.

vi. Social + Commercialization of Remanufactured Product

Due to the long remanufacturing life cycle and technology advances, some products become obsolete faster either functionally or psychologically, thus making it difficult to be sold once it re-enters the market. For this reason, a fashion-based product was rarely remanufactured. It has been a challenge for remanufacturing company to ensure the attractiveness of remanufactured product in terms of functionality, technological and psychological aspects. In Section 3.3.4.iv (Technical + Commercialization of Remanufactured Product), we have discussed this issue from a technical perspective. Hence, this discussion focused on the attractive commercialisation from a social point of view. Well-educated consumers on the true concept of remanufacturing were among the important action to be considered, since previous researchers had proven that there was always a negative perception of remanufactured products. Interesting marketing program, good services and facilities, effective and efficient contracts, and interesting promotion were some of the solutions that can boost sales of remanufactured products. The company is suggested to determine the needs, wants, and interest of target markets (Kotler et al., 2005) and also customers' purchasing habits in order to realise the above solutions.

Another constraint was on the human right protection for both customers and remanufacturing companies (or company that sell remanufactured product). It included purchasing contract, warranty, and product's information/promotion (i.e. fraud) issues. Competition with other companies was not the reason for them to violate the human rights. The marketing department has to know remanufactured product condition and capacity and targeted customers' profile in order to achieve an optimum and safe marketing program. There were some companies that offer customers a warranty testing and failure mode analysis where the product was inspected and tested per customer requirement. Full report documentation was then provided back to the customer where all critical characteristics were analysed.

4 Pillars SD	6 Aspects Rem System	Characteristics	Implementation (product or process)
Social	Design for reman (product)	Specific expertise (easy future remanufacturing)	Designer's knowledge and motivation, formation, visits, guideline, brainstorming, Contract of warranty, product quality, Intellectual property
		High motivation	
		Possible to give warranty	
		Safe to be remanufactured (ownership issue)	

	Reverse supply chain	Encourage the client to return and bring the suppliers close to the remanufacturing company	Contract , return programme/management, promotion, guideline, management, awareness program
		Respecting the rights of remanufacturers and customers	
		Socially safe working environment	
	Information flow in reman system	Collaborating with suppliers and others in the chain,	Communication and cooperation, training and formation, enforcement
		Good networking,	
		Smooth communication	
	Employees' knowledge and skill	Well trained employee	Worker's profile, human resource management, training,
		High level of consciousness	
		Specific task for specific workers skill level	
		Attractive task (job satisfaction)	
	Reman operation	Socially safe working environment	Enforcement, housekeeping, Communication
		Stakeholders share and give feedback, suggestion	
	Commercialization reman product	Meet customer expectation,	Customer's satisfaction, product and company's image, promotion, education, marketing program, services, contract, environmental impact communication, local business communication, Contract, management, warranty, information, Patent of reman process, PSS business model
		Good image	
		Interesting and convincing	
Respecting the rights of remanufacturers and customers			
Consumer trust in reman product = new			

Table 5: Remanufacturabilities from social perspective

3.3.4. Remanufacturability from Technical Perspective

As stated in the previous chapter, technical, technological, and design aspects played a critical role in remanufacturing industry. Technical feasibility appeared to be an important decision factor on whether a product was able to be remanufactured or not. Identifying this concern during the design phase may facilitate a proper and simple reprocessing at the end of its life. In this section, descriptions of the identified technical characteristics in every element of remanufacturing system were presented.

i. Technical+Design for Remanufacturing

From the design and technical perspective, the essential characteristic was to determine whether a product was possible to be remanufactured or not. From the existing academic articles, a product that had the following criteria was possible to be remanufactured technically. These criteria may help designers in defining their remanufacturable product:

- Have a core (Statham, 2006; Lund, 1984).
- Cannot be consumed in its use (Lund, 1984).
- The original function of the product and its level of performance can be restored by remanufacturing (Statham, 2006; Lund, 1984).
- The product has failed in its functionality (Lund, 1984).
- The product must have a reasonably long useful life (Lund, 1984).

Another factor that may affect the above criteria was the customer's behaviour in the used phase that determines the condition of the product in its end-of-life. A more severe condition of the product at the end of its life was something to be expected, and may hinder remanufacturing process. Leasing and product service system may be a favourable solution to reduce extra-damages condition of the used products.

Customers would hesitate to pay a high price for equipment that may become rapidly obsolete due to technological change. Thus, products with a mature stage of technology would be more suitable to be remanufactured compared to the growth-stage products (McConocha & Speh, 1991). A stable or mature technology means, "A technology that has been in use long enough that most of its initial faults and inherent problems have been removed or reduced by further development" ("Mature technology", 2016). Motor vehicle, watch, and bicycle are some examples of mature technologies, while the internet and the computer are the examples of not-yet fully mature technologies. Nanotechnology, nuclear fusion power, and quantum computers are the examples of new and immature technologies that need further and deeper research and development.

Knowing the technological stability of a product was necessary to determine remanufacturing compatibility and duration of the product's first life. From the technical perspective, the shorter the original life expectancy, the higher the probability of the product to be remanufactured (McConocha & Speh, 1991). A shorter first life expectancy may reduce the risk of the unpredictable future.

Another characteristic that exists under the design and technical perspective was durability which means; having a long useful life (Lopez Ontiveros, 2004) and hardly damaged during its use (Ijomah et al., 2007) including corrosion resistant (Amezquita et al., 1995). These characteristics may increase the possibility of a product to be remanufactured because it is technically easy to be repaired (less difficult operation would lead to less operational time and less operational cost). Type of material, product's form, manufacturing operation, and fastening method may determine the durability of a product. However, in order to satisfy the majority of the constraints, designers have to make a hard decision for a contradictory constraint. For example, a more durable material will normally need more cost or add more difficulty to work on for a repair operation. Therefore, it is important to consider each trade-off carefully and compare what will be gained or lost by each option. This issue was discussed in detail later.

Upgradable is another characteristic that might help remanufacturing activity in the future. It is a long-term investment in order to attract and satisfy future customers. Product characteristics such as a modular system (Lopez Ontiveros, 2004), standardise components, interface and fastener (Amezquita et al., 1995), and systematic internal/external arrangement might increase the upgradability of a product.

ii. Technical+Reverse Supply Chain

Reverse supply chain from technical perspective plays a significant role in determining the remanufacturability of a remanufacturing process. Constraints in the technical aspects of a reverse supply chain system can be manageable incorporating several strategies: 1) a planned and a formalized logistic network and system (Barquet et al., 2013); 2) a good alignment of the direct and reverse supply chain (Barquet et al., 2013); 3) a good input and output control (Barquet et al., 2013); 4) a well-determined safety stock level; and 5) the length of the planning horizon (Ferrer, 2008). According to Rogers et al. (2013), an efficient reverse logistic starts by clearly understanding its nature and applying the guiding principle, which is simplification. Given that much of this product is low in value, it is important to simplify the process, shorten the time and distance of transportation, and eliminate the unnecessary touches. Simple act like having an identical and neatly stacked boxes and pallets is an example to achieve the stated goals (Rogers et al., 2013). Giving a

sufficient and attentive concern on the management of reverse supply chain may increase economic, environmental, and social profit of remanufacturing system.

According to Tseng et al. (2005), transportation occupies one-third of the amount in the logistics cost which made transportation system to become the key element in a logistics chain. This constraint is extracted from a wider constraint of manageable that has been previously discussed, and it will be discussed separately. From product perspective, this constraint helps designer to think about transport constraint that may affect products' characteristics such as products' form, dimension, and material. The aim is to have an easy and safe transportation activity.

From process point of view, an effective packaging and storage system (durable, standardize, and reusable), optimum lot size, transport type, and capacity may increase production's speed, reduce product's damage, and render and easier operation.

iii. Technical+Information Flow in Remanufacturing System

From technical perspective, a manageable flow of information in remanufacturing system can increase remanufacturability. It includes an accurate and good control of information (Barquet et al., 2013), a coordinated data collection (Lindkvist, 2013), and a system that allowed feedback to be routed-back to companies for reflection and improvement (Ferrer, 2008). According to Barquet et al. (2013), from remanufacturing process perspective, the following information must be managed by remanufacturers:

- which product should be returned to the remanufacturer,
- when will these product arrive,
- where are these products located,
- how many of these products can be remanufactured.

Another concern that falls under technical aspect of information management is the ability to determine component's condition easily. It is a necessity for remanufacturers to have adapted trekking device and monitoring system. Some may suggest applying electronic tracking device whenever possible (Ferrer & Clay Whybark, 2000). This constraint not only allows an easy operation, but also facilitates forecasting and reduces uncertainty.

iv. Technical+Employee's Knowledge and Skill

Knowledge and skill in remanufacturing should be technically transferrable to ensure long term sustainability of a company. It is important for companies to formalize and

standardize remanufacturing operation for management reason as well as facilitating knowledge and skill transferring. Since it is difficult to get loyal employees that remain in a company, a documented guidelines and operations are essential for future employees. One of the solutions in the effort of handing over skills is to implement an apprentice program between experienced workers with new employees for certain duration of time.

v. Technical+Remanufacturing Operation

Disassembly process is important for the early position in remanufacturing activity as remanufacturing cannot occur without it (Priyono et al., 2015). Remanufacturing operation usually requires disassembly process to retrieve high value cores within a product. Therefore, products that are designed intentionally for disassembly and remanufacturing will be used to facilitate disassembly operation, avoid excessive damage, and save time and cost (Amezquita et al., 1995).

In order to achieve these goals, Soh et al. (2014) suggested several design requirements:

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

According to Soh et al. (2014), DfD should consist of three aspects, which are the adoption of suitable methodologies, implementation of technologies, and incorporation of human factors (ergonomics) consideration (See Figure 19).

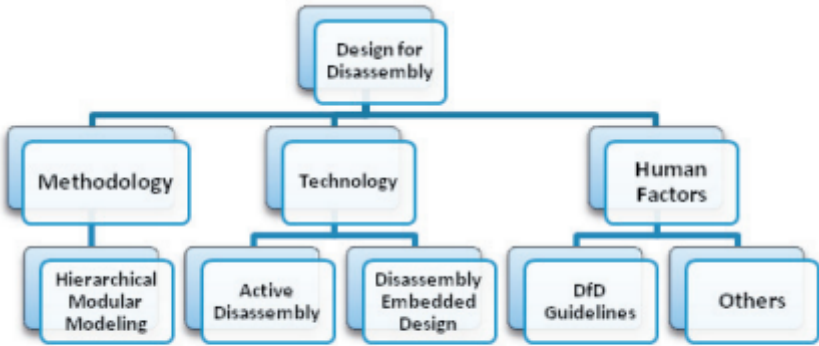


Figure 19: Three aspects of Design for Disassembly (Soh et al. 2014)

DfD guidelines serve as a basic reference for designers during product design. In the guidelines by Dowie and Simon (1994), they suggested to minimize the number of fasteners and number of required removal tools. Besides that, it should be easy to remove the fasteners and to access the fastening point.

As for disassembly methodologies, most of the academic proposals are based on the hierarchical modular modelling which can be utilized for disassembly sequence planning such as the graph representation (De Mello & Sanderson,1990) and the Petri-Net (Moore et al., 2001). The objective is to determine an optimal disassembly sequence based on the shortest route to reach the core and the geometric constraints of the product. However, it is not enough to solely apply disassembly methodology as it does not address the practical problems faced during disassembly such as space limitation and tools accessibility (Soh et al., 2014).

The advancement of disassembly technology could profit remanufacturers in terms of quick and simultaneous unfastening fasteners by using smart material. Besides that, the assembly embedded design and active disassembly (AD) might enhance disassemblability. It might also reduce human effort and time besides solving space limitation problem. Regarding human aspect, other than integrating ergonomic factor, a clear disassembly instruction might also increase employees' understanding.

The main purpose of cleaning is to facilitate inspection and damage correction besides making the parts to be in a new condition. The process of cleaning requires one or multiple processes including both manual and machine operations. From technical perspective, a product that is easy to be cleaned (form, dimension, material, type of contaminant) and has a good resistant to go through cleaning operation (high melting point, wear resistant). For cleaning procedure, there are several requirements that could support cleaning operation such as similar and efficient cleaning procedure and cleaning agent, clear cleaning purpose, and definite technical cleanliness requirements. The consideration on this constraint during the design process of a product increases the ability to be cleaned and remanufacturability.

Sorting operation means operation that specifies which returned items should be remanufactured or scrapped. Technically, product's aptitudes allow easy identification, easy sorting decision making, and less sorting operation time which are considered to have good sortability from product's perspective. On the other hand, sorting operation from process's

perspective is affected by the variety of returned product's conditions. According to Lu (2009), it is a challenge for remanufacturers in making the following decisions:

- How many used items should be acquired?
- How selective should the sorting process be?
- How many remanufactured products should be kept in inventory for future demands?

In general, a less stringent sorting will generate more available cores, and the return rate should also be less. However, this lower selectivity may require sophisticated recovery technologies and also a higher per unit recovery cost. Finding an optimal acquisition/sorting policy by considering the interaction between these two factors might facilitate remanufacturer and avoid unnecessary loss (Lu, 2009). Multiple stages of sorting procedure, starting by performing the simplest and cheapest inspection operations are able to simplify workers' tasks (with easier inspection criteria) and enhance sorting quality (Errington and Childe, 2013).

Recoverable is a constraint that implies the possibility or feasibility that can be restored to its original specification for reuse. From product perspective, a good recoverability means having a capability of being replaced easily, preventing damage during part insertion, allowing a minimum replacement time, and having a bulkier parts to allow rework. Some strategies like label and number parts, giving an easy access to things that are most likely to break or need replacement, sticking with standard component whenever possible may help in achieving the above objectives. It is also crucial to select a proper material and fastening method to determine product recoverability.

A high reassembleability of a product is depended on the performance of reassembly for components that is easy and less time consuming. This can be achieved by applying an optimal fastener's method, structuring component arrangement, and choosing an optimal component's tolerance. From process perspective, reassembly operation is highly affected by inventory management. Reassembly operation can be facilitated through the assurance of product's availability by managing inventory.

Once a product is repaired and reassembled, it will pass through the final stage of the inspection procedure, which is the product testing stage. In this stage, the product's reusability is assessed by inspecting its performance and it is treated individually to allow a correct performance for each unit. Surveys by Hammond et al. (1998) showed that 21% of

participants have difficulties in identifying defects in cores during inspection operation. Therefore, a good testability of a product should allow easy identification and testing operation. A standardize testing procedure that is developed in conjunction with the OEM might increase testability. According to Errington and Childe (2013), a hundred percent inspection is potentially unnecessary at the final stage, but it is always done for assurance.

A mapped and formalized operation management is another characteristic for technical aspect in remanufacturing operation. Companies that analyse and evaluate operation and performance regularly might reduce problems and increase efficiency. Besides that, the application of adaptable tools and approaches might also help in mapping and formalizing remanufacturing operation.

vi. Technical + Commercialization of Remanufactured Product

From commercialization of remanufactured product’s perspective, technically manageable signifies a systematic and effective product’s remarketing operation. The above objectives can be achieved by mastering technology facilities (i.e., internet), tracking performance and using appropriate managing tools.

4 Pillars SD	6 Aspects Rem System	Characteristics	Implementation (Product or Process)
Technical	Design for reman (Product)	Have a core	Design, reuse cycle, usage condition, product lifetime (first, total)
		Cannot be consumed in its use	
		Original function of the product and its level of performance can be restored by remanufacturing	
		Not/slightly change over the years	Technology cycle, product lifetime (first, total)
		Slowly evolving technology	
		Long useful life	Material, form, manufacturing quality, fastening method
		Hardly damaged	
		Corrosion resistant	
		Modular component, fastener, interface	Material, fastening methods, product structure (dimension, form), internal arrangement
	Standardisable component		
	Integration of several stakeholders constraints	Networking, integrated design	
	Reverse supply chain	Planned logistic network,	Logistic network, merge with direct supply chain
		Determine the safety stock levels and the length of the planning horizons	
Easy to be transported		Transport and storing system (container),stock size, type of transport,	

			schedule, distance
		Aggregate parts early to avoid transporting useless item	Storage system, stock condition, product features
		Enough storage space	
		Good storage	
		Easy supply of spare parts	Additive manufacturing
		Ensure core supply	PSS business model, pay back
		Select core for reman before they are considered as waste	
Information flow in reman system		Easy and early determination of component condition (traceable)	Information system, tracking device, forecasting, material flow
		Allow feedback to be routed back	
		Good control/coordinate of information	
		Accurate information	
		Long term product data management	
		All stakeholders have access on product information	Networking
Employee knowledge n skill		Transferrable knowledge and skill	Standardize and documented operation and guidelines, apprentice, Collaborate with other stakeholders
reman operation		Easy to disassemble	Number of components, fastening method, disassembly force exertion, tool requirement, positioning and accessibility, connectivity complexity, DfD guidelines and instructions
		Allow complete disassembly	
		Allow non-destructive disassembly	
		Efficient disassembly process	
		Minimum disassembly time	
		Minimum number of fastener	
		Easy to be cleaned	Number of components, surface type , material, form/shape, component arrangement, cleaning procedures, cleaning agent , lot size, cleaning purpose
		Minimum cleaning time	
		Material with higher melting point	
		Minimum variety of material	
		Similar and efficient cleaning procedures and cleaning agents	
		Wear resistant	
		Corrosion resistant	
		Good cleaning quality	
		Easy to sort/inspect	
	Minimum time		
	Easy access	Part accessibility, Fastener accessibility	
	Capable of being replaced easily	Part material and	

		Prevent damage during part insertion	fastening methods, machine
		Minimum replacement time	
		Minimum function for every component	
		Bulkier parts (more material) to allow rework	
		Easy supply of spare parts	Additive manufacturing
		Easy to reassemble	Number of components, tolerance
		Minimum reassembly time	
		Easy to be handled	Form/shape, number of components
		Easy identification	Material, component arrangement, test procedure
		Mirroring reassembly order	
		Standardize test procedures	
		Mapped	Lean remanufacturing operation (time, machine, material, lot size, energy)
		Formalize operation	
Commercialization reman product	Easy to manage	Marketing system	

Table 6: Remanufacturabilities from technical perspective

3.4. Validation

In order to validate this proposition, this study has collected feedbacks from designers and remanufacturers on the relevancy of the 2DFR concept and the proposed definitions of remanufacturability. The obtained knowledge and experiences could improvise, enrich, and validate the proposition of this dissertation. Therefore, a survey was conducted in a workshop slot during Grenoble's European Remanufacturing Network (ERN) event, which was attended by designers, consultants, remanufacturers (OEM and IR), and academicians (Masters and PhD students, lecturers) from European countries. The one-day event was filled with presentations of several academicians on circular economy and remanufacturing challenges and practices, and there was a session on the sharing of industrial feedbacks from a few remanufacturing companies, a workshop, a forum, and networking dinner.

The workshop slot was reserved for this study, and is mainly focused on the remanufacturing concerns encountered from the 2DFR and issues on remanufacturing tools. The workshop started with a short briefing on the topics and explanation on how to fill a worksheet provided by the organizer (see Annex B), followed by a 50-minute session for

participants to complete it, and a 20-minute discussion and restitution marked the end of the schedule.

3.4.1. Validation Worksheet

During the workshop, the participants were given a worksheet with the following compositions:

- a. Introduction of 2DFR: Presentation of the elements presents in both dimensions.
- b. Remanufacturability matrix: Presentation of 6x4 table, aggregation of company's concerns, applicability of the provided remanufacturability information. It is associated to the first proposition of this dissertation, for validation purpose
- c. Remanufacturing tools: Survey on tools and methodologies used by participants and arranged in a 6x4 table, details on the used tools/methods, and questions about their opinions regarding the scarcity of remanufacturing tools/methods and the important characteristics of a tool/method. It focuses on the second proposition of this dissertation, which is the study of remanufacturing tools and methods.
- d. The participants' profile: Information about their position, business sector, company's activities, and duration of remanufacturing experience.
- e. Annex: The information in remanufacturability table.

The following are the objectives for the worksheet distribution:

- Introduce the 2DFR.
- Allow users to classify remanufacturing concerns using the introduced framework, in order to test participants' understanding on the introduced concept. This result may yield the actual concerns of remanufacturing stakeholders after many years of research and technological advances within the sector. Introduce and validate the theoretical objectives and the implementation means of the remanufacturability matrix.
- Survey the remanufacturing tools and methodologies used by the participants.
- Know the type of tool/method that designers/remanufacturers need.
- Know the important characteristics that a tool must have from a user's point of view for future invention.

3.4.2. Participant's Composition

The workshop had gathered 24 worksheets from the participants with the following details:

- 11 participants were academicians, while 13 were professionals
- The distribution of the 13 professionals:
 - 5 participants were consultants
 - 3 were OEMs
 - 2 were third party remanufacturers
 - 1 was an independent remanufacturer
 - 2 others
- The distribution of the 13 professionals:
 - 6 were products-based activity
 - 6 were services-based activity
 - 1 was involved in both activities
- The distribution of academicians:
 - 2 persons with 5 to 10 years experiences
 - 1 person with 2-5 years experiences
 - 2 persons with less than 2 years experiences
 - 1 person with zero experience
 - 5 persons who did not indicate their experience
- The distribution of professionals:
 - 5 companies with more than 10 years experiences
 - 3 companies with 5 to 10 years experiences
 - 1 company with 2-5 years experiences
 - 1 company with less than 2 years experiences
 - 3 companies with zero experience

3.4.3. Worksheet Analysis

In this section, the results from the “Remanufacturability Matrix” section are collected and analysed. As for the section on “Remanufacturing Tools”, the results are explored in the beginning of Chapter 4. This analysis is based upon the answers given in the worksheet by the people who attended the workshop. It is important to note that not all

participants completed all the questions given or responded the way that organizer want it to be answered More particulars were gathered during the discussion and from the notes left in the worksheets given.

i. Remanufacturability Matrix

In this section, the participants were asked to choose and rank 4 cells usually cause remanufacturing concerns. Giving weight for the answers (4 point for the most important concern and 1 point for the least important concern), the following Table 7 is the total result:

	1. Economic	2. Environmental	3. Social	4. Technical	Total
a. Design for remanufacturing	18	19	6	14	57
b. Reverse supply chain	21	5	0	1	27
c. Information flow in reman system	4	0	0	10	14
d. Employee's knowledge and skills	0	4	3	5	12
e. Reman operation	14	20	1	16	51
f. Commercialization of reman product	23	10	3	1	37
Total	80	58	13	47	

Table 7: Result from participants regarding remanufacturing concerns that they faced

Scoring legend	
	21 and above
	16-20
	11-15
	6-10
	1-5
	0

The following are the conclusions deduced from the given results:

- The economical factor of the commercialization aspect marks the highest concern
- The economical factor in employees' knowledge and skills, the environmental factor in information flow aspect, and the social factor in reverse supply chain and information flow aspects mark the lowest scores respectively.
- The economical factor poses the most concern in remanufacturing activity, while social factor is the least concerning issue.
- From the remanufacturing system's perspective, design for remanufacturing and the remanufacturing operation aspects become the highest concerns for the respondents while information flow is the lowest concern.

Economic factor becomes the most important factor in remanufacturing activity, while social factor becomes the least factor in remanufacturing concern. This conclusion validates the statements given by researchers regarding economic influence in remanufacturing activities. From remanufacturing system's perspective, design for remanufacturing and remanufacturing operation becomes the highest concern for the participants. This might be due to the participant's background as half of them are researchers.

Besides that, participants were also requested to ascertain the theoretical objectives and the means of implementation in the provided annex, and they could give comments for any missing point. The answers from participants are gathered, revised, compared, and added in the provided annex. Overall, the participants agreed with the theoretical objectives and the implementation means. However, many of them find it difficult to discern an issue as it was linked with more than one perspective.

ii. Analysis and discussions

As mentioned earlier, the first part of the worksheet aims to validate the relevancy, applicability and practicality of the 2DFR and the theoretical definition of remanufacturabilities from 2DFR:

- The classification exercise has trained the participants to identify the remanufacturing concerns in their company/work and to put them in the 2 dimensional matrix. This work was different from the previous with only one-dimension. It took more time and efforts to complete this exercise. Thus the 50 minutes given to complete all the questions during the worksheet fill-out session were not sufficient for all. However, during the discussion session which began with collecting the results verbally from each participant, all the participants correctly gave answers as instructed. This had proven that the 2DFR concept was understandable and applicable for a real usage.
- In the second exercise, the contents in the remanufacturability table were verified by the participants. Some participants had suggested some remanufacturing constraints in the remanufacturability table. The latest version of remanufacturability table had considered those suggestions and can be considered as a validated and applicable table.

However, remark such as the difficulty to distinguish a multi-related constraint was arisen from 1-2 participants during the discussion session. This remark may due to the insufficient time to digest, reflex and classify the new introduced concept without denying that it may appear irrelevant to some people.

No participant has mentioned that the remanufacturability table could be very useful for design and decision making checklist. It only provides a near-to-complete list of remanufacturing constraints from 2 dimensional perspectives. The more experienced companies had raised concerns from politic and regulation aspects which is not precised in the propositions. For them, politics and government have an important influence on business strategy, remanufacturing law and market. Therefore emphasizing their role in the remanufacturing framework seems crucial to support remanufacturing sector in the future.

3.5. Discussion and conclusion for proposition 1

This chapter has successfully introduced and validate a two-dimensional framework for remanufacturing and a remanufacturability table functioning as a guideline for designer and remanufacturer. These propositions contribute in highlighting remanufacturing constraints from each element of sustainable development. This allows to consider them early in the decision making process and in the design phases of the products. This proposition has responded to the first research question on **“How to characterize remanufactured product and remanufacturing system from a sustainable development perspective”**. With this proposition, it seems that the OEMs are in a more favourable position to perform remanufacturing than the independent remanufacturers, where the authority to access early information on a product is a competitive advantage.

The remanufacturability table is served as a guideline to design a remanufactured product for sustainable development. The advantages and disadvantages of this guideline compared to the previous significant existing guidelines are as below:

a) Advantages:

- Compared to remanufacturing guideline by Ijomah et al. (2007) which focuses on remanufacturing process; and remanufacturing guideline by Amezcua et al. (1995) which focuses on remanufacturing and design process, our proposition offers a wider and more comprehensive aspects of remanufacturing system.
- With regard to the other guidelines which normally focuses on the economic and technical aspects, or focusing only on one aspect (i.e.: environmental aspect), our proposition covers the four aspects of sustainable development including social aspect which is classically ignored by companies/designers.
- The two-dimensional concept integrates and classifies both perspectives simultaneously for a more precise concern. This precision may facilitate stakeholders in detecting problems for further action.
- Our proposition offers a more specific and well-classified constraints and implementation ideas, which can be used directly by designer/remanufacturer.

b) Disadvantages:

- Since it covers wider and multi-perspectives constraints, our proposition may seem longer and tedious to go through. It may not be suitable to use in a short and brief company's meeting.
- This proposition is not solving the integration issues as mentioned in the research by Ijomah et al. (2013).
- This guideline remains subjective and non-quantitative.

To sum up, in this chapter, the following findings can be used as a guideline to create remanufactured product for sustainable development:

- Two-dimensional remanufacturing framework
- Characteristics of remanufactured product for sustainable development
- Suggestion of implementation for every characteristics
- Validation study on the relevancy, applicability and practicality of the above propositions.

These findings should help designers and remanufacturers in designing and planning process. One of the approaches that might help designers/remanufacturers in the above activities is the application of remanufacturing tools and methods to achieve the maximum characteristics of remanufactured products for sustainable development that were listed in the proposition table. The study and proposition about remanufacturing tools and methods that use the new proposed framework in this chapter is described in the next chapter.

Chapter 4 (Proposition 2): Method to Classify and Choose DfRem Tools/Methods

4.1. Findings from the survey on “Remanufacturing tools” during the ERN workshop

4.1.1. Survey’s objectives

As mentioned in the previous chapter, the results from the survey on “remanufacturing tools” are presented here, to highlight the importance of a method to classify and choose DfRel tools/methods. Revisiting the objectives of “Remanufacturing Tools” section in the worksheet (subchapter 3.6.1 – annex B), questions were asked to identify the utilization of tools and methodologies, and of how far remanufacturing tools/methods influence a participant’s remanufacturing activities. These objectives were identified to give some ideas in positioning this research and to help to orient the actual research in remanufacturing tools/methods domain, according to the needs of remanufacturing stakeholders. Four questions and exercises were provided to the participants as follows:

- a) Using the 2DFR matrix, participants are asked to complete the table with the tools/methodologies that operate within their companies/workings’ environments.
- b) Participants are asked to specify the type of tools/methods that have been listed in their previous answer.
- c) Participants are enquired about necessary but lacking characteristics of the tool/method
- d) Participants are questioned about the important characteristics that tools/methods must have.

4.1.2. Results

Question a

Respondents are requested to fill in the table with information regarding the remanufacturing tools and methodologies used by them, with respect to the 2DFR classification. The list of tools/methods table 8, classified into the topmost and the farthest left end of the 2DFR matrix are the tool/method that can be used for all the corresponding cells of the column (i.e. the LCC tool for economic purpose) and row (i.e. the Granta Design

for design for remanufacturing element) respectively. Otherwise the tools/methods listed in the top left corner cell indicate the tools/methods that can be used in all the cases . The gathered results are as following (See Table 8):

		LCC	LCA tools, MFA, ISO 14001	Social LCA, social impact assessment	BOM
	Production system, quality system (ISO, BSI)	1. Economic	2. Environmental	3. social	4. technical
Design tools, Granta Design	a. Design for remanufacturing	LCCA, standardization, legislation, reverse engineering	Repro2		open design, DfX, modularity, material selection,
	b. Reverse supply chain	logistic tools, optimization, analogic simulation, excel+forecast placement, operational management			
Industry 4.0	c. Information flow in reman system				SI, SAP, PLM, IMDS
Knowledge management	d. Employee's knowledge and skills		Training, accompanying	recognized expertise	graphic approach
Lean remanufacturing, process optimization	e. Reman operation	MFA, KPI, lean reman	LCA, ISO1400, clean reman, lean reman, MFA, value stream analysis		technical cleanliness standard and guidelines, manufacturing standard, product documentation
Accounting spreadsheets	f. Commercialization of reman product	Eco label, ISO	Ecolabel	Social network	

Table 8: Remanufacturing tools/methods used by the participants classified in the 2DFR matrix

Question b

In this section, participants are asked to emphasize whether the tools/methods announced in (a) are strategic or operational tools/methods. The results show that:

- Both types of tools/methods have been used by both the industrialists and academicians participants.
- Most of the used/suggested tools/methods are the general tools/methods, which usually helps instrategic purposes

According to the feedbacks, usually industrialists utilize the general tools/methods in the strategic tasks but usually developed their own specific tools for operational tasks.

Question c

In this section, respondents' opinions are gathered on the topic of remanufacturing concerns that lack of tools. The results are as follows:

- a) 7 respondents highlighted the lack of forecasting/assessing/estimating tools in various remanufacturing concerns.
- b) 3 respondents stated regarding the shortage of marketing tools.
- c) 3 respondents issued a need of communication tools amongst both the internal and external stakeholders.
- d) 2 respondents specified about the lack of training and education tools for employees.
- e) 2 respondents thought of the necessity for tools that gather and allow information sharing.

Question d

Respondents are asked to list the salient characteristics that a remanufacturing tool must own. The summary is as follows:

- Majority of respondents wish to have simple and easily handled remanufacturing tool (8 out of 18)
- Adaptable, upgradeable and easy to access to data are some characteristics mentioned by more than 1 respondent.
- Some respondents prefer multi-criterion /multi-pillars tools.
- Some respondents wish tools that include explanation, definition, and examples, rather than having tools that presents a single answer.

4.1.3. Analysis and remarks

Respondents' answers in sections a, b, c and d provide important insights into remanufacturing tools and methodologies used by stakeholders of various positions in remanufacturing community. Below are some of the significant remarks that can be used to highlight the importance of the second proposition, in addition to the arguments as noted in the literature review.

- From the data in table 8, it is apparent that the tools and methodologies used/suggested by the participants are mostly the general ones.
- From respondents' answer in a, b, c and d, it is merely a circumstantial evidence of remanufacturing tools actually being applied in the industry. Whereas in reality, these recent years have seen the surfacing of, more and more tools and methodologies introduced by many researchers to tackle remanufacturing concerns and optimize remanufacturing system.

To conclude, there is a vital need to provide a method that will help remanufacturing stakeholders to intelligently find existing and relevant tools/methodologies from the academic realm, and to be applied according to its relevancy. This problem is in accordance with the objective of these tools' creation, which is to be used and applied for better remanufacturing agenda.

4.2. Research Method for Proposition 2

Based on the aforementioned problem statement and research question, we included discussions on our research method as presented below.

a) We conducted a broad literature study on DfRem tools and methods in order to: i) recognise research trends; ii) identify their similarities and differences; iii) understand their objectives and concepts; and iv) allow the configuration of a possible classification method. Detailed information on DfRem tools/methods is included in the previous chapter. The research parameters gained from this literature are as follows:

- Type of tools/methods to be analysed: DfRem operational decision making and optimisation tools/methods
- Type of analysis approach: input and output analyses

b) We conducted a content analysis on the existing DfRem tools/methods. DfRem tools/methods with respect to the defined parameters in (a.i.) were analysed using the developed methods in (c).

c) We developed two interdependent DfRem methods using the 2DFR from the previous chapter. The methods are:

- A classification method, which allows DfRem tools/methods to be classified systematically by creating some working tables and rules
- A method that facilitates designers to choose DfRem tools/methods based on the remanufacturability table from Proposition 1 and results from the classification method (i).

d) We proposed illustrated study case studies to demonstrate the usage of the developed methods and configurator.

e) We presented results and discussions.

4.3. Delimitation of the Method: Strategic, Tactical, Operational or Optimisation Tool/Method

In the former chapter, DfRem tools/methods are reviewed as design aids that help designers to solve certain remanufacturing problems. The review on the DfRem tools/methods is specific to the operational planning and optimisation tools/methods. The review is again applicable in this proposition 2 as we intended to define the decision making tool (strategic, tactical and operational) and optimisation tool.

In mathematics and computer science, the decision and optimisation problem are differentiated using the following elaborations:

- Decision problem: A question with a yes-no answer
- Optimisation problem: A problem of finding the best solution from all feasible solutions

Remanufacturing decision making tool was then classified based on the decision stages by Goodall et al. (2014) and the classifications are as follows:

- Strategic decision stage and tools: This is a high level decision making stage and it is aimed to shape the long-term future of a business. In remanufacturing context, this stage is usually taken to review whether the remanufacturing has the desired effect

on the business. Strategic tools are designed to assist decision makers in assessing remanufacturing feasibility at a strategic level. These tools evaluate the suitability of the products, business and the internal suitability for remanufacturing (Goodall et al., 2014).

- Tactical decision stage and tools: This stage tends to be focused toward the medium term, with the aim of providing a method for implementing the chosen strategy. It assesses remanufacturing in order to determine which product to be considered for remanufacture. Tactical tools aim to evaluate a particular designed product in order to determine the appropriate end-of-life strategies for its individual components. The difference between this type of tools and the operational tools is that Middle of Life effects are neglected (i.e.. the condition of the returned product). The usage of these tools is to evaluate the best practice for remanufacturing facilities at the end-of-life stage and product design stage (Goodall et al., 2014).
- Operational decision stage and tools: This stage is usually encountered on a daily basis. The aim of this stage is to assess the possibility to remanufacture individual products/components and remanufacturing facility through product inspections where the products are filtered. Operational tools are used to evaluate a specific product for remanufacture, e.g., during inspection phase (Goodall et al., 2014).

In this study, we referred to the same concept in differentiating the decision making and optimisation tool/method. However, it is also true that optimisation tool/method can help user to make his decision. With the later statement, it is not easy to classify them. As we selected designers as our focus group, we would only implicate the tools/methods to be used after the senior/upper management decide whether to remanufacture a product or not. Then, the type of tool/method that is included in this study is the operational decision making tools/methods and the remanufacturing optimisation tools/methods. The strategic decision making tool/method is a category clearly excluded from this study as referred to the definition proposed by Goodall et al. (2014). Later in this chapter, we included explanations on the inability of applying our proposition to the strategic DfRem tools/methods due to compatible issue. Besides, the strategic tools/methods normally take into account every aspect of decision factors and it is difficult to classify. Moreover Goodall et al. (2014) proposition seems very relevant for this issue.

4.4. List of Analysed DfRem Tools/Methods

The existing tools and methods within the above delimitation are used as the inputs of our second proposition, which is the method to choose and classify the existing DfRem tools and methods. Table 9 presents the list of the 12 tools/methods with different types and various characteristics to test the compatibility of our proposed method. Each tool will be described in the following paragraphs. This study was conducted within the engineering domain because of the familiarity and speciality reasons, and thus, the analysed tools/methods were gained from the engineering-based journals.

	Approach	Author(s)	General @ specific	Format	Qn @ Ql
1	CLOEE	Gehin (2007)	Specific	Software	Quantitative
2	Recore	Sifert et al. (2013)	Specific	Software	Qualitative
3	RNDM	Kizilboga et al. (2013)	Specific	Calculation	Quantitative
4	Cleaning method	Liu et al. (2013)	Specific	Reference	Qualitative
5	EIS	Ismail et al. (2014)	Specific	Software	Quantitative?
6	MGE	Tchertchian et al (2014)	Specific	Calculation and conceptual	Both
7	DFTPR	Wu et Kimura (2007)	Specific	Calculation and conceptual	Quantitative
8	Rempro matrix	Sundin (2004)	Specific	Reference	Qualitative
9	Metrics dfrem	Bras and Hammond (1996)	Specific	Calculation	Quantitative
10	Metrics dfrem	Fang et al. (2014)	Specific	Calculation	Quantitative
11	Reliability and cost optimization for reman process	Jiang et al. (2016)	Specific	Calculation	Quantitative
12	R-DFLP	Li et al. (2015)	Specific	Calculation and conceptual	Quantitative

Table 9: List and main characteristics of the 12 tools/methods analysed in this thesis

4.4.1. Close Loop Environmental Evaluation (CLOEE)

The current Life Cycle Analysis (LCA) tools do not really support the closed-loop analysis, especially when there are many closed loop strategies to be tested (e.g., reuse, recycle, and remanufacturing) with different options (Jorge Amaya, 2010). In order to facilitate the evaluation of environmental impact on the closed-loop life cycle product, Alexis Gehin et al. (2007) created Close Loop Environmental Evaluation (CLOEE) in 2007. It is an ecodesign tool that integrates the methodology of product life cycle analysis bricks with

multiple use cycles. This software proposes a product model that allows users to consider the recovery strategies for components by taking into account several usage phases. It helps designers to create different life scenarios for products under design. It also provides the comparisons between the environmental impacts for the different designed life cycles. This software is available online with English as its medium of communication.

CLOEE functions like a calculation sheet. So firstly, users must calculate the impact assessment of the life cycle bricks for the product under studies using the normal LCA software. A life cycle brick has two dimensions, i.e., a lifecycle dimension and a product/component dimension. Users need to key-in these data in CLOEE and define the calculation. The calculation of environmental impacts of different combinations for the end-of-life phase becomes faster and easier. Nonetheless, it is essential for the users to have a good grasp on the LCA tools and ways to read/interpret the environmental impact data before they can use it.

4.4.2 Research for Efficient Configurations of Remanufacturing Enterprises (ReCORE)

The next online tool named Research for Efficient Configurations of Remanufacturing Enterprises (ReCORE) is related to a European research project that aims at managing high variety and complexity of remanufacturing. This research centred in Bayreuth University, Germany was completed by Sandra Seifert et al. in 2013. Its goal was to enable executives of remanufacturing companies to find information on applicable complexity drivers, and to select appropriate optimisation strategies in order to manage complexity effects, tailored to their needs. ReCORE's function and content were validated in an expert workshop by representatives of remanufacturing companies.

According to Lundmark and Sundin (2009), uncertainty and complexity are the most challenging factors in remanufacturing. However, approaches for managing complexity specific to the needs of the remanufacturing industry are yet to be revealed (Seifert et al., 2013). Therefore, a new methodology for a successful complexity management based upon detailed knowledge on complexity drivers and effects should be developed. Based on identified drivers and effects, a configurator containing key performance indicator (KPIs) and optimisation methods for measuring and managing complexity effects in remanufacturing companies was set up.

This was done by keying-in company's specific parameters and choosing complexity effects, which are occurring in the user's company. Next, the users would be presented with related drivers that cause the effect, methods that are suitable to manage the effect, and related KPIs that enable the users to measure the management success. Users can choose up to 50 complexity effects considered applicable by him in his company during the configuration session. Text boxes with short information on effects and methods are available to provide support in making the selection. In addition, the users are provided with basic knowledge on complexity occurring in companies and are provided with links for further references and related topics.

4.4.3 Remanufacturing Network Design Modelling (RNDM)

Remanufacturing Network Design Modelling (RNDM) is a mathematical model for a reverse logistic network design and it was developed by Gozde Kizilboga in 2013 (Kizilboga et al. 2013). This research initially aimed to design and develop a Reverse Logistic Network System that contains remanufacturing processes for a heavy truck manufacturer in order to remanufacture their diesel particulate filter (DPF). Reverse Logistic (RL) processes in the closed-loop life cycle strategy require energy consumption. Therefore, it is very important to determine optimal geographical locations of remanufacturing centres as it contains economic and environmental impacts as cost function in the mathematical model based on Capacitated Facility Location Problem approach. The costs are represented by two indicators, which are financial amount (economic indicator) and carbon dioxide emissions (environmental impact indicator).

This tool allows the designer/manager to answer these questions:

- How many remanufacturing centres are required?
- Where should the geographical location of manufacturing centres be located?
- What is the appropriate capacity of remanufacturing centres?
- Which service point should serve and from which remanufacturing centre?
- What is the amount of investment?

The required data for the model are: i) demand of each service point; ii) opening cost of new remanufacturing centre; iii) transportation cost; and iv) reprocessing cost. RNDM is written using Java-Cplex® and the results are obtained using Eclipse®. The optimal location

and the number of remanufacturing centre are obtained as a result of different capacity essays. This tool is recommended to the OEM to design their network systems.

4.4.4 Cleaning Method

Cleaning is among the demanding steps and it is a particularly essential process in remanufacturing because clean surface indicates the quality of the core and it influences the proceeding process. Remanufacturing cleaning is considered the main source of pollution in the remanufacturing process. Even though remanufacturing cleaning is a crucial step but it is often neglected during remanufacturing process optimisation. In 2013, WeiWei Liu et al. (2013) developed a remanufacturing cleaning method in order to cater the aforementioned problems. Therefore, this research was conducted to establish a foundation for further study on remanufacturing cleaning process.

The cleaning method is very useful for designers and remanufacturers to assist them in planning their cleaning activity. The followings are basic cleaning principles.

- Identify cleaning purpose and technical cleanliness requirements. Here, the authors present five cleaning steps in each phase of remanufacturing with different purposes and requirements in each stage.
- Recognise the core contaminant type and its attachment manner.
- Choose the appropriate cleaning method and cleaning agent according to the material, quantity, geometric dimensions of the core to be cleaned. Evaluate any possible damage of the cleaning agent to the product's surface, the cleaning efficiency, and required cost.
- Evaluate energy consumption, waste discharge (including waste gas, wastewater, waste oil, and solid waste) according to the environmental requirements, and ensure to reduce resource consumption and environmental pollution.

These principles would assist the designers/remanufacturers to decide, to start, and to consider the appropriate cleaning activity. Besides cleaning method, information on the basic elements of remanufacturing cleaning, the categories of cleaning forces, the common cleaning mediums, and remanufacturing cleaning technology is also included. This information is essential in the creation of this cleaning method and it is a real adds for the future for cleaning optimisation and standardisation.

4.4.5 Environmental Impact Simulator (EIS)

Another remanufacturing project is the Environmental Impact Simulator (EIS) and it was created in the SimaPro to help designers/remanufacturers quantify environmental burdens and potential impacts of their remanufacturing activity (Ismail et al., 2014). A remanufacturing function was created under the “processing” category, and it contains the data from the Remanufacturing Process Library. Remanufacturing Process Library works like a catalogue, where almost all information about the major methods and technologies for the remanufacturing process is gathered. In this library, the generic parameter for each process is calculated using the linear slope method and used in the EIS.

Basically, users simply have to choose the remanufacturing process, key-in their product size parameters (e.g., weight, volume), choose the consumable material, key-in the consumable material parameters, and change the duration of the cycle (depending on the type of the product). Next, the software performs the calculation and the results appear in a few minutes. This tool is still under research and development, but the beta-version is available at the G-Scop laboratory. It is recommended to use this tool in the early stage of design to help designers/remanufacturers in choosing the minimal environmental impact method/technology among those that exist. It helps designers/remanufacturers to reduce the environmental impacts of their remanufacturing activities.

4.4.6 Modular Grouping Explorer (MGE) Tool

The Modular Grouping Explorer (MGE) is a design tool created by Tchertchian et al. (2013) and it is used to modify the current product architecture (PA) in order to design products that can be remanufactured (See Figure 20). This tool is not yet implemented as a software, but an Excel interface was developed to facilitate the internal deployment. The objective of MGE is to optimise the end-of-life option by grouping modules/components according to the characteristics of their life cycle. This tool works based on three basic principles, which are:

- Modification of current product architecture by questioning module frontiers
- Characterisation of initial modules/components by predefining whether they can be remanufactured or recycled according to the criteria of cost and environmental impact

- Grouping modules by calculating their affinity (reliability, obsolescence and compatibility between materials)

Two types of grouping can be envisaged from this tool, which are i) the recyclable modules (pMr) and ii) the Remanufacturable modules (pMR). Three main properties are retained for grouping the modules/sub-modules, which are:

- Homogeneity of the materials
- Reliability/maintainability
- Technical and visual obsolescence

Modules with low obsolescence and high reliability are always considered for remanufacturing. This module can be further classified in two sub-modules that apply the same rules. Next, affinity coefficient is calculated among and between the modules or/and sub-modules using affinity equations of the three properties stated earlier. This approach helps designers to predefine the modules upstream during the design process. MGE tool gives a better result as compared to other simple end-of-life scenarios optimisation tools that do not cover the full architecture of the products, its modules and components.

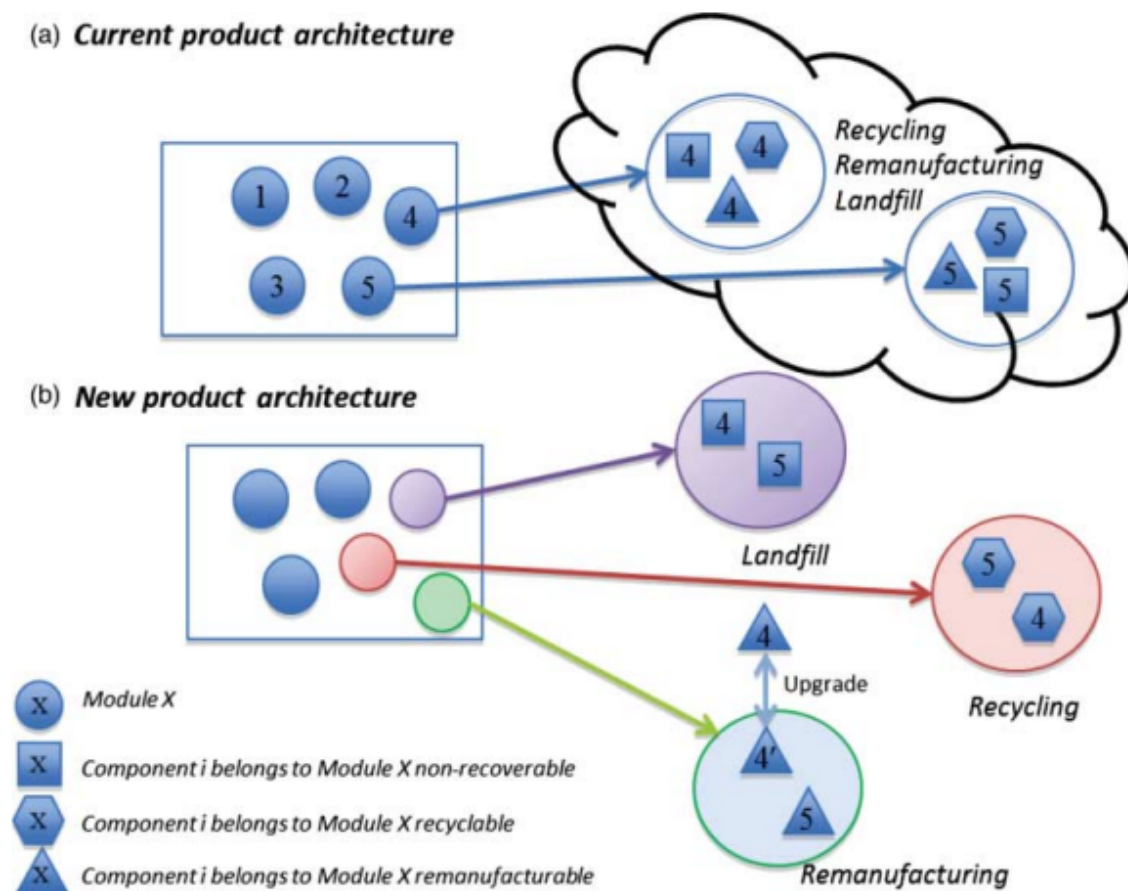


Figure 20: The concept of MGE tool which is used to modify product architecture (Tchertchian et al. 2013)

4.4.7. Design for Product Taken-Back Parts Reuse (DfTPR)

According to Wu and Kimura (2007), reusing taken-back parts into new products is a challenging task for designers. In reusing taken-back parts, there are more design constraints compared to the classic design process. This is because designers have to concurrently consider product requirements and think of how to select and reuse taken-back parts. Therefore, this method was developed for the conceptual design stage in order to help designers to select an optimise feasible conceptual design in terms of the structure, process, quality, and cost requirements. This method presents a new mathematical method for both aspects of product conceptual design. The aspects are Functional design and Structural conceptual design.

The relationships between structural and functional conceptual designs are represented using a structure-function mapping Boolean matrix (See Figure 21). Besides, a constraint diagraph was also developed to represent constraint relationships among all the structural elements. All feasible design schemes, which satisfy the functional requirements, are derived from the matrix and the diagraph (See Figure 22). This method proposes an eco-cost calculation of reused parts in order to get an optimal design scheme, which satisfies technical requirements, and to make the best of reusing taken-back parts.

		F1	F2	F3	F4	F5	F6
Upper die seat	P1					•	
Upper tie plate	P2					•	
Upper dead plate	P3					•	
Upper die	P4	•					
Lower die	P5	•					
Lower dead plate	P6					•	
Lower tie plate	P7					•	
Lower die seat	P8					•	
Guide plate	P9				•		
Guide sleeve	P10				•		
Guide post	P11				•		
Unload spring	P12			•			
Rubber	P13			•			
Unload bot	P14			•			
Elastic unload plate	P15			•			
Dead unload plate	P16			•			
Baffle bolt	P17	•					
Baffle pin	P18	•					
Locating plate	P19	•					
Nut	P20						•
Socket head cap screw	P21						•
Cylindrical pin	P22						•

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Figure 21: Boolean Matrix (Wu and Kimura 2007)

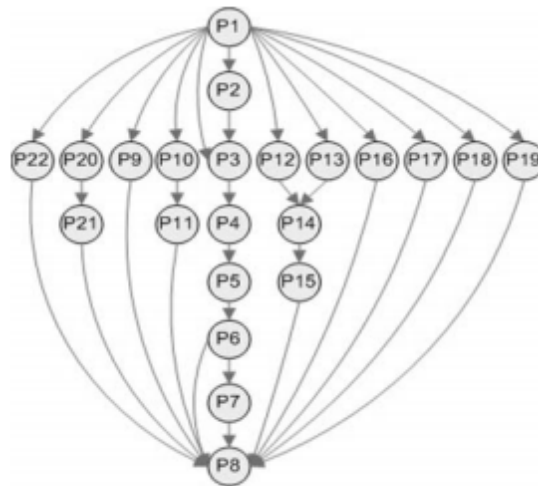


Figure 22: Diagram G of product structural element

4.4.8. Rempro Matrix

The Rempro matrix (Figure 23) is a reference format tool and it was developed from a study by Sundin (2004). This matrix shows the relationship between remanufacturing steps and product properties, such as ease of identification, ease of handling, and ease of verification. It functions as a reference and guidance for designers in the prioritisation issues. This matrix helps designer to identify which product properties to be prioritised in order to obtain an efficient results from remanufacturing since remanufacturing process often includes many steps. The more relationship between both elements exists, the more important the properties become. Therefore, designers should focus on the more important properties if they have to choose only some of them.

Product Property \ Remanufacturing Step	Inspection	Cleaning	Disassembly	Storage	Reprocess	Reassembly	Testing
Ease of Identification	x		x	x			x
Ease of Verification	x						
Ease of Access	x	x	x		x		x
Ease of Handling			x	x	x	x	
Ease of Separation			x		x		
Ease of Securing						x	
Ease of Alignment						x	
Ease of Stacking				x			
Wear Resistance		x	x		x	x	

Figure 23: The Rempro Matrix by Sundin (2004)

4.4.9. Metrics for Assessing Remanufacturability (MAR)

Based on the well-known Design for Assembly metrics approach, Bras and Hammond (1996) developed metrics for assessing the remanufacturability of a product design. These metrics aim to efficiently and effectively measure the mechanical remanufacturability of product designs based on the features of the product designs. These metrics are composed with the top-level issues, which include the following sets of metrics:

- Damage Correction that composes of repair, refurbishment and replacement metrics
- Cleaning
- Quality Assurance that composes of testing and inspection metrics
- Part Interfacing that composes of disassembly and assembly metrics

Finally, a pertinent formula to calculate the remanufacturability index is given respecting magnitude, idealisation, annihilation and weighting criteria. Figure 24 shows the remanufacturing index for Kodak funsaver camera, which was presented as a case study during the research.

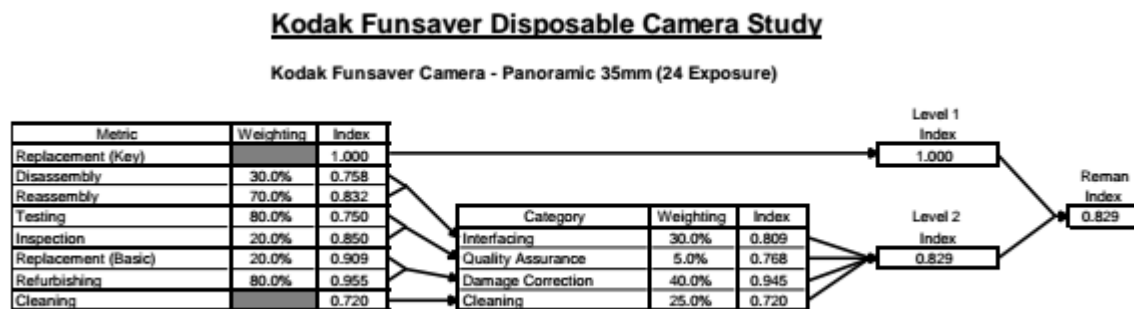


Figure 24: Summary of Metric Indices for Kodak Funsaver Camera (Bras & Hammond, 1996)

4.4.10. Remanufacturability Assessment Metrics Based on Design (RAMBD)

Remanufacturability assessment of a product design aims to evaluate the feasibility of a product/component to be remanufactured based on the information of the product design. Similar to the previous metrics concept, Fang et al. (2014) developed a new set of remanufacturability assessment metrics that integrates design information from CAD models, such as bill of material, assembly and mating features, dimensional and tolerance features. These metrics allow designers and decision-makers to gain insight on the product design and view the different aspects that influence product remanufacturability in the early design stage. Four metrics were proposed to evaluate remanufacturability, which are:

- Disassembly complexity metric, Mcom
- Fastener accessibility metric, Macc

- Disassemblability metric, M_{dis}
- Recoverability metric, M_{rep}

4.4.11. Reliability and Cost Optimisation for Reman Process (RCORP)

One of the major challenges faced by remanufacturer is to assure the reliability of the remanufactured products since they came with varying conditions. Moreover remanufacturing process always involves several demanding remanufacturing steps, such as disassembling, cleaning, reconditioning, reassembling and testing. Jiang et al. (2016) suggested that process planning plays a critical role in realising a successful remanufacturing strategy since it directly affects the success rate of remanufacturing as well as reliability and cost. Therefore, Jiang et al. (2016) proposed an optimisation method for remanufacturing process planning that takes into account the reliability and cost of remanufacturing process. Reliability is determined through the failure rate of remanufacturing operations, which is dependant on the quality of returned used cores. The process cost includes machine cost and tool cost. Subsequently, a genetic algorithm was used to solve the multi-objective optimisation problem, which is to provide remanufacturing process with maximum reliability and minimum production cost. As a result, the optimal operation sequence and the information for the optimal process plan would be obtained. The presented method not only provides the optimal remanufacturing process planning, but also decision support for high reliability remanufacturing.

4.4.12. Remanufacturing Dynamic Facility Layout Problem (R-DFLP)

Uncertainty in remanufacturing is a well-known factor that complicates remanufacturing activities. Some of the issues that become challenges to design and arrange remanufacturing facility layout are products quality, products quantity, product return time, and its processing time for remanufacturing operation. Therefore, Li et al. (2014) aimed to cater these challenges with a tool to optimise remanufacturing dynamic facility layout problem (R-DFLP) by achieving overall high efficiency and minimising cost. Facility layout problem (FLP) concerns with resource localisation for a well-coordinated workflow. Therefore, optimising FLP may benefit remanufacturer since FLP has a direct and indirect influence on matters like material handling cost, working-process inventory, and leads times.

There are two types of FLP, which are static and dynamic. The type of FLP depends on the nature of the input requirements and the time periods under consideration. Static layout

is usually performed for a single time period and it assumes the flow between machines, the product demand and the level of product mix are constant. Given the nature of remanufacturing environment where uncertainty is inevitable, one time period may not be efficient for successive others. Thus, R-DFLP deals with dynamic FLP, in which it is modelled by discretising the time into several planning periods. The simulated annealing algorithm was used to resolve the optimisation problem with variable process capacities, unequal processing cells, and intercell material handling. As a result, a dynamic multi-row layout model with minimisation of both material handling cost and machine relocation cost is presented in Figure 25

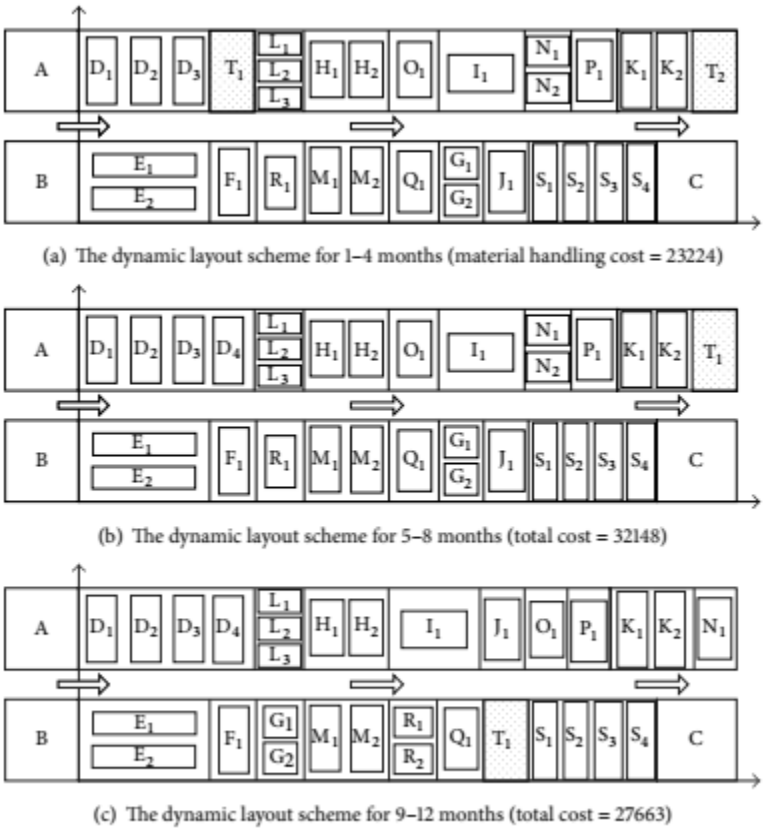


Figure 25: The result of R-DFLP that shows a dynamic layout scheme for a whole year with the estimated cost (Li et al., 2014)

4.5. Classification Method for DfRem Tool/Method (Ismail et al., 2014)

The first component of the second proposition is the methodology to identify and classify the existing tool/method. From all the classification methods mentioned in the previous chapters, we chose to classify the existing tools/methods from the perspectives of sustainable development and remanufacturing system. The elements of the sustainable

development (economic, environmental, social, and technological) are the factors that would influence the decision-making process. While the elements of remanufacturing system represent the area and the usage stage of the analysed tool/method. Both perspectives are among the useful criteria for designers/remanufacturers in choosing a tool.

This methodology uses the input and output perimeters of the analysed tools/methods. It consists of a two-steps analysis using two types of tables, which are the individual tool analysis and the two-dimensional analysis grid. Tools/methods listed in Table 9 were analysed using this methodology. In this section, we include the description of the steps, and how to use the tables. The results of the analysis are presented later in this chapter.

4.5.1 Input and Output Parameters Approach and Their Definition

Input-output analysis is a method that shows how some parts of a system are affected by a change in a part of that system. In this study, we analysed the input and output parameters of DfRem tools/methods as an approach to identify and classify them. This approach was chosen in order to allow a simple, direct and formalised analysis. Normally, the input parameters of tools/methods are available in the literature and could be used straightforwardly. Contrarily, the outputs parameters are not usually stated directly and easily confused with other elements such as tool/method function, goal and objective. For this reason, a study to define those terms was conducted to identify the output of a tool/method. In the context of the tool/method, the basic descriptions of those terms are as follows:

- Output: What does a tool/method deliver?
- Function: What does a tool/method do?
- Objective: What is aimed by a tool/method in achieving mid to short-term goals and specific actions?
- Goal: What is the purpose of a tool/method towards an endeavour is directed, normally for a longer term and generic action?

We consistently stuck to the aforementioned descriptions while defining the output of each tool/method. This was to ensure a direct, non-interpreted and standardised output identification process. Table 10 shows some tools/methods outputs, functions, objectives and goals to emphasise their differences.

Tool	Output	Function	Objective	Goal
CLOEE	Environmental impact of closed-loop end-of-life scenario	Calculate environmental impacts of different end of life scenarios	Test/compare many closed loop strategies with different options	To help designer to choose eol scenario that has a minimum environmental impact
			Help designer to create different life scenarios for products under design	
Recore	Tailored set of optimization methods	Identify complexity drivers and effects	Manage complexity in a systematic way	To enable remanufacturing companies to handle complexity induced effects on the remanufacturing process by providing adapted and newly developed optimization methods
	Kpis	Quantify complexity drivers and effects	Allow users to select appropriate optimization strategies for managing complexity effects tailored to their needs	
	Information on complexity drivers & knowhow	Assess/evaluate whether a method is suitable or not to avoid/reduce or handle complexity		
RNDM (Gozde)	Numbers of required remanufacturing centre	Minimize all expense during the reverse logistics network construction	To determine optimal geographical locations of remanufacturing centres by considering economic and environmental impact as a cost function in the mathematical model	
	Geographical location of manufacturing centre	Convert the cost function into environmental impact		
	Capacity of remanufacturing centre	Choose the optimum capacity among different possibilities		
	Which service point should be served from which remanufacturing centre			
	Amount of investment			
Cleaning method (Liu)	Appropriate cleaning method	Introduce the fundamental concept of remanufacturing cleaning technology	To find out the optimize cleaning method	Realize the real green remanufacturing
	Appropriate cleaning agent	Describe the major cleaning		

		technologies		
	Cleaning efficiency			
	Cleaning cost			
	Cleaning agent damages to the part surface			
	Analyse energy consumption, discharge of waste			

Table 10: The differences between outputs, functions, objectives and goals

With the reference to the above definitions, we move on to the table of analysis for different tools/methods.

4.5.2. Individual Tool Analysis

The Individual Tool Analysis table was created to analyse the input and output parameters of a tool/method from the perspectives of sustainable development and remanufacturing system. By referring to Figure 26 for the input analysis and Figure 27 for the output analysis, these tables consist of the criteria from the sustainable development concept by Fatimah et al. (2013) and the remanufacturing system by Barquet et al. (2013). The first column of each table is filled with input (or output) tool parameters revealed in the literature, while the rest of the table is the analysis cells with the calculations at the bottom rows.

After the identification of input and output parameters, each parameter was analysed by giving it a score marked in the appropriate cell. The rules are as follows:

- One score is given if the parameter is directly related to both elements of the sustainable development and the remanufacturing system.
- Half a score is given if the parameter is indirectly related to those elements.
- No score is given if the parameter is not related to the element, or related to only one element.

It is important to follow these rules to ensure the cross-correlation between the two perspectives. Therefore, it is very important to be well-informed of the definitions of every element suggested by Fatimah et al. (2013) and Barquet et al. (2013). It is also important to have basic information related to the elements.

Definitions of the Elements in Remanufacturing System by Barquet et al. (2013)

Element 1 - Design for Remanufacturing: This element is about product characteristics at product development stage with the aim to ease the future of remanufacturing process. In other words, this element functions to facilitate an efficient remanufacturing operation. In addition to the classic product characteristics, Ijomah et al. (2007) included other aspects, which are the technological changes, the business model of services and the environmental legislation.

Element 2 - Reverse Supply Chain (RSC): The RSC begins with the collection of products from clients and/or companies in different links of the supply chain, and collection sources tend to be geographically dispersed. This element also involves inspection or tests performed at the collection site, at a receiving centre, or at the site where the product will be reused. At this point, a decision is made about the destination of the collected product, which presents various possibilities include reusing and remanufacturing (Kopicki et al., 1993). Besides, this element includes the relationship between the used product supplier and the reverse logistics (the activities of transportation, storage, and distribution of the products).

Element 3 - Information Flow in the Remanufacturing System: According to Thierry et al. (1995), information related to product return management can be classified into four categories, which are:

- Information on the composition of the product: types of material, the quantities, value, potentials of harmfulness to nature, and the ways of combining the different types of materials
- Information on the magnitude and uncertainty of the return flow according to the type of commercialisation chosen for the product: traditional sale, leasing, and rental
- Information on the market for remanufactured products: the perceived difference in the quality and cost between the remanufactured products and new products, the affects, and the acceptance of these products
- Information on how returned products are currently done: an analysis on the involved organisations, the obstacles, the quantity of the remanufactured product (for each returned product), the costs, and the overall environmental impact of the remanufacturing system

Element 4 - Employees' Knowledge and Skills in Remanufacturing: This element consists of the issues of the employees from contacting the supplier, collecting the cores (transport, storage), remanufacturing operation phase (e.g., inspection, disassembly, and cleaning), to

selling the remanufactured products. The employees should be perfectly familiar with the remanufacturing system in order to tackle every issue appropriately at every stage. Besides, qualifications and trainings of the employees are also included in this element.

Element 5 - Remanufacturing Operation: The remanufacturing operation begins with the arrival of the cores at the remanufacturer's facilities. Next, the cores will go through several stages including disassembling, cleaning its parts, inspecting, reconditioning of the parts that will be reused, replacing components that cannot be remanufactured, assembling, and lastly gaining a remanufactured product. Then, this product is tested to ensure that its quality is equivalent to a new product (Ijomah et al., 2007).

Element 6 - Commercialisation of the Remanufactured Product: This element encompasses aspects of sales, distribution, and customer relationship. Additionally, it explores potential market segments and strategies to increase the attractiveness of remanufactured products, such as warranty and complementary services. The marketing studies include this element with the clients' profiles, buying behaviour, and their perceptions towards the product.

Definitions of the Elements in the Sustainable Development by Fatimah et al. (2013)

Economic: life-cycle costs, sales, rebates, and subsidies

Environmental: environmental criteria, such as solid wastes and greenhouse gases emissions

Social: education, subsidies, employment opportunities and warranty period

Technological: Technical criterion involves the reliability of the remanufactured products, such as the material, method, man, machine, energy and information. The appropriate technical feasible solutions include the best available technologies, processes, technical skills, energy consumption, and material consumption.

Since the definitions of the elements of the sustainable development by Fatimah et al. (2013) are not well-elaborated, this study refers to the description available in the previous background chapter.

When recording our data for this study, we set-up the analysis cells of the table with an automatic colour change when the score is keyed-in. The cell changed its colour into red when the score is one, and green when the score is 0.5. Next, the total score was

automatically summed-up and divided by the total number of parameters (input or output) in order to transform it into a percentage. If the obtained result is higher than 30 per cent, then the tool is considered to have an influence on the related element. We chose the 30 per cent value arbitrarily since there was neither previous research nor evidence in the literature review discussing this issue. We consider 30 per cent as our first attempt value and it is subjected to discussion in the future if needed. Again, this table automatically changed colour into orange when the percentage cell is 30 per cent and above. To demonstrate, Figures 26 and 27 show the examples of CLOEE analysis.

As depicted in Figure 26, there are nine input parameters of CLOEE. Each parameter was analysed, and the result shows that the CLOEE input parameters are mostly related to design for remanufacturing element from the technical and environmental aspects. In Figure 27, the outputs of CLOEE are the environmental impacts of closed-loop end-of-life scenario. The outputs of CLOEE were analysed to determine whether they are related to the aspects of design for remanufacturing, information flow, and remanufacturing operation in remanufacturing system from environmental perspective. From this analysis, we can interpret that the output analysis represents the real function of the analysed tool/method. Later the input parameters would be useful as the information to configure an appropriate tool/method to facilitate designers in choosing tool/method.

Input	Sustainable development				Remanufacturing system					
	Eco	Env	Soc	Tech	design for reman (product)	reverse supply chain	information flow in reman system	employee knowledge n skill	reman operation	commercialization reman product
A. CLOEE										
1 Number of component				1	1	0.5	1		1	
2 Environmental impact of component's material	1	0.5			1					
3 Environmental impact of component's manufacturing	1	1			1					
4 Environmental impact of component's distribution	1					1				
5 Environmental impact of component's reuse										
6 Environmental impact of component's remanufacturing	1		1		1	1	1	1	1	1
7 Environmental impact of component's recycling										
8 Environmental impact of component's incineration										
9 Environmental impact of component's landfill										
Total	0	4	0	3.5	4	2.5	2	1	2	0
percentage	0%	44.44%	0%	38.8%	44.44444444%	27.77777778%	22.22222222%	11.11111111%	22.22222222%	0%

Figure 26: Individual Tool Analysis for CLOEE Tool's

matrices of the eleven other tools/methods are available in Annex C. In the section for results and discussion (4.6), a superposed matrix will be presented by summing up the twelve analysed tools/methods.

	CLOEE Input						CLOEE Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic												
2. Environment	1						1	1		1		
3. Social												
4. Technical	1											

Table 11: Analysis Grid for CLOEE Input and Output

4.5.4. Results and Discussion for DfRem Classification Method

The expected results for this method are shown in Table 11 for CLOEE tool on the representation of the two-dimensional analysis grid for each analysed tool/method. The results for the other tools/methods are available in Annex C. In this section, the two-dimensional analyse grid is presented on the superposed output parameters as the additional application of this method. The results of the superposed output parameters allow some analysis and interpretations on the analysed tools/methods. It can be used as important information especially in creating new tool/method in the future by focusing on the least explored area.

Table 12 shows a combination of all the output matrices for all the 12 tools/methods. Each cell of Table 12 contains the number of tools tackling this issue. This is calculated by

summing up the matrix obtained for each individual tool. The last column contains the total values of every sustainable development aspects for every cell, and the last row shows the total values of every element for the remanufacturing system for every cell. According to the table below, it can be concluded that there is the lack of tool (or method) in all aspects of the sustainable development for the commercialization of remanufactured product and employees' knowledge and skills. Besides that, the social aspect is the last treated aspect among the existing tools. Despite the gaps, there are many tools that tackle the remanufacturing operation issue especially for technological aspect. This may be due to this study's domain of the research area that focused more on engineering domain. If the research area is widened to the other domain, there is a high possibility to expect different results.

	1	2	3	4	5	6	Total
Ec	2	2	6	1	5	0	16
En	3	1	5	0	5	0	14
So	0	2	2	1	1	0	6
Te	4	2	9	1	9	0	25
Total	9	7	22	3	20	0	

Table 12: The Superposed Output Parameters for All Analysed Tools/Methods

It is clear that the above table does not represent the actual condition of DfRem tools/methods as there are only 12 analysed tools/methods. However, it represents the function of the proposed methods which is to capture the existing expertise. It is hypothesised that the more analysis done on tools/methods, the more information will be obtained on the condition of the existing DfRem tools/methods.

4.6. A method to Choose DfRem Tools/Methods

The actual problem related to the academic DfRem tools/methods is that they exist in the form of mathematical models and software tools/methodologies, which are more complex to be used (Hatcher et al., 2011). For this reason, it is found that not many designers/remanufacturers use these tools/methods. Moreover, it is a challenge for designers to choose the tool that fit their needs due to the abundance number of existing

DfRem tools/methods besides the upcoming new methods. Therefore, the second part of this proposition aims to help designers in choosing the appropriate DfRem tools/methods based on their needs. By using the framework and remanufacturability table in proposition 1 and the previous classification methods, this method provides users with useful and accurate information about the tools/methods within a short time. In terms of principle, this method will suggest the appropriate existing and analysed tool(s)/method(s) based on the objective that the users want to achieve. It could also become a medium to introduce the academic DfRem tools/methods to the industrial users in a guided and systematic way.

4.6.1. DfRem Tool's/Method's Outputs in Remanufacturability Table

This section will describe in details the concept of choosing method and its connection with the previous proposed methods (definition of remanufacturability and the classification method). The remanufacturability table, which provides the various objectives of remanufacturability aspects, is used to classify the existing outputs of DfRem tools/methods. At this stage, those outputs are easily available as they have been defined and classified in the previous classification method (the individual tool analysis and the two-dimensional analysis grid). In order to classify these outputs, the following steps have been applied:

- a. The result from the classification method of tools/methods output is used as the first approach to identify the related area that a tool/method is meant for. For example, the environmental sections in the remanufacturability table on the design of remanufacturing and information flow are verified for CLOEE.
- b. The tool/method output is then compared with the remanufacturability objectives in the related area. The output that matched the remanufacturability's objective were classified in that objective. For example, CLOEE's output (the environmental impacts of the end-of-life scenario) is classified under the objective of "possible to pre-assess/assess the environmental impact" which is one of the objectives of environmental + design for remanufacturing and environmental + remanufacturing operation area.

The (a) and (b) steps have been essentially applied for others tools/methods because it is the easiest and fastest methods to be used to classify the outputs. However, in order to be safe, this study added the third step in (c) to ensure the outputs are appropriately classified.

c. This step is used to compare the list of the remanufacturability objectives with the tools/methods output. For CLOEE, its output serves the following objectives:

- “Well-educate and well-guided customer on environmental issue” from the environmental + commercialisation of reman product area.
- “Interesting and convincing” from the social + commercialisation of reman product area.

Even though this step requires a lot of effort, it can also function as a verification step for the previous method.

Figure 28 visualizes the steps to construct this method including the above steps by organizing the steps in a structured diagram for a clear and better understanding.

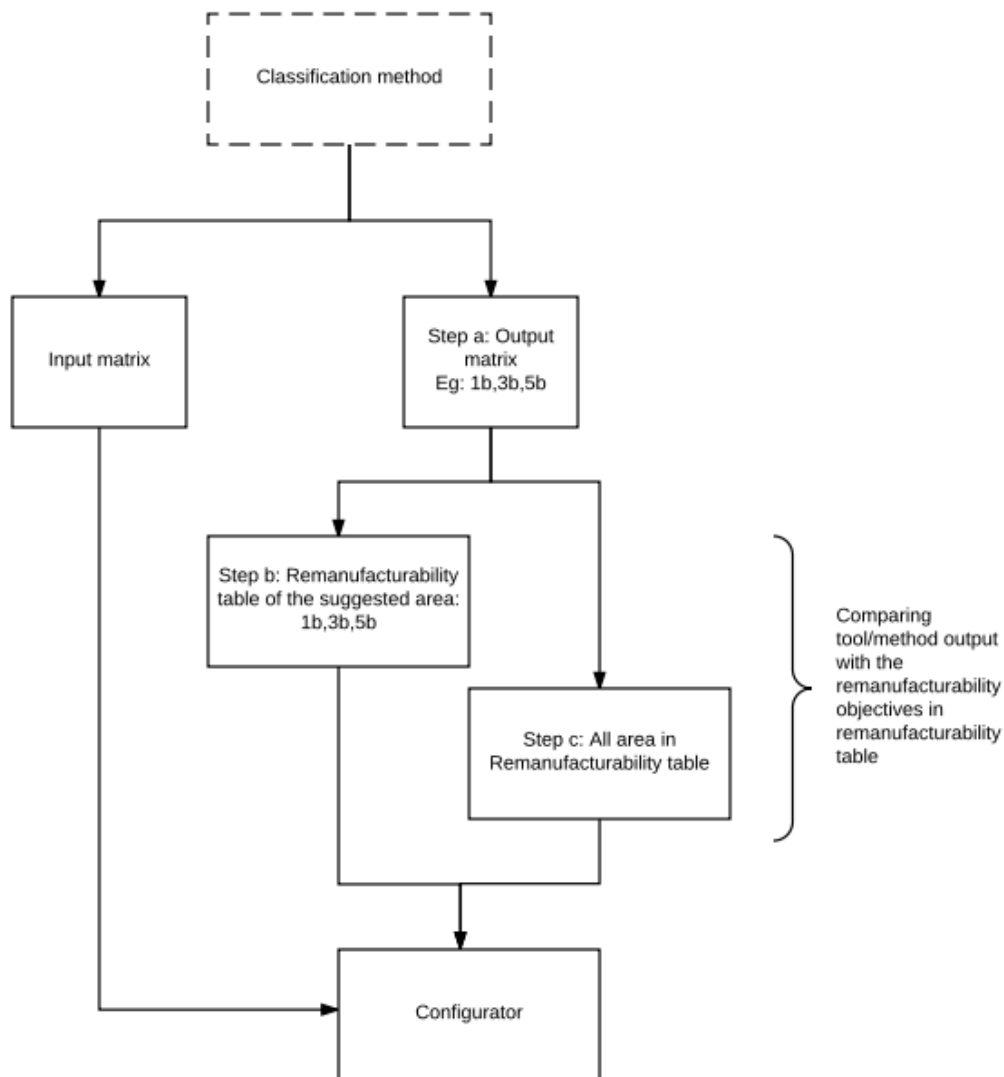


Figure 28: Diagram that shows the flow to classify the input and output of a tool in the remanufacturability table to be used as a database for the configurator of the Choosing Method

4.6.2. The Choosing Method from Users' Point of View: The Configurator

This section will explain this method from users' point of view as the approach to construct this method is different from the approach faced by the users. In fact, the previous method of classification and the construction of the choosing method have indirectly created a database of Dfrem tools/methods. During this study, a configurator was developed to allow user manipulation. The following are the two functions for this configurator:

- a) An interface for user to apply the choosing method.
- b) An interface for the classification method where user can key-in the new tool/method in the database and analyse it manually.

i. Interface to Choose DfRem Tool/Method

As mentioned before, the main goal of this method is to help designer to choose existing tools/methods by referring to the sustainable development and the remanufacturing system perspectives with the company’s objective. Figure 29 shows the first interface of this configurator where user has to choose a specific cell to see the available tools/methods.

Pillar/Aspect	Design for remanufacturing	Reverse supply-chain	Information flow	Employee knowledge and skills	Remanufacturing opération	Commercialisation
Economic						
Sociologic						
Environnemental						
Technologic						

Figure 29: The First Interface of the Choosing Method

Once the cell is clicked, a window will pop-up which contains other information for user to choose the next criteria which is the remanufacturability’s objectives. Figure 30 shows the pop-up window for the environmental + design for remanufacturing cell. In the objective’s button, user can choose the specific objective that he or she wants to achieve. These objectives correspond to the remanufacturability table in proposition 1.

Figure 30: The List of Objectives for Environmental + Design for Remanufacturing

Once the objective is chosen and clicked, the available tools/methods are listed in the “available tool/s” button. In Figure 31 below, the CLOEE tool is available for the “possible to pre-assess/assess environmental impact” objective. The inputs of CLOEE are available in the “implementations” button, while the outputs button shows the output of CLOEE. This information is essential for the users to decide whether the proposed tool is suitable or not with the inputs that they entered as well as the output that they expect.

The screenshot shows a window titled "UserForm1" with a red border and a close button in the top right corner. The window contains four main sections:

- Objectif:** A dropdown menu with the selected option "Possible to pre-assess/ assess environmental impact".
- Outils disponibles:** A list box with "CLOEE" selected and highlighted in blue.
- Implementations:** A text area containing the text "Number of component, EI of every phase of the life-cycle".
- Outputs:** A text area containing the text "Comparison of the environmental impacts of differents end-of-life scenario".

Figure 31: The Window that Shows the Information for CLOEE Tool

Figure 32 shows the diagram on how to use this method from the users’ point of view.

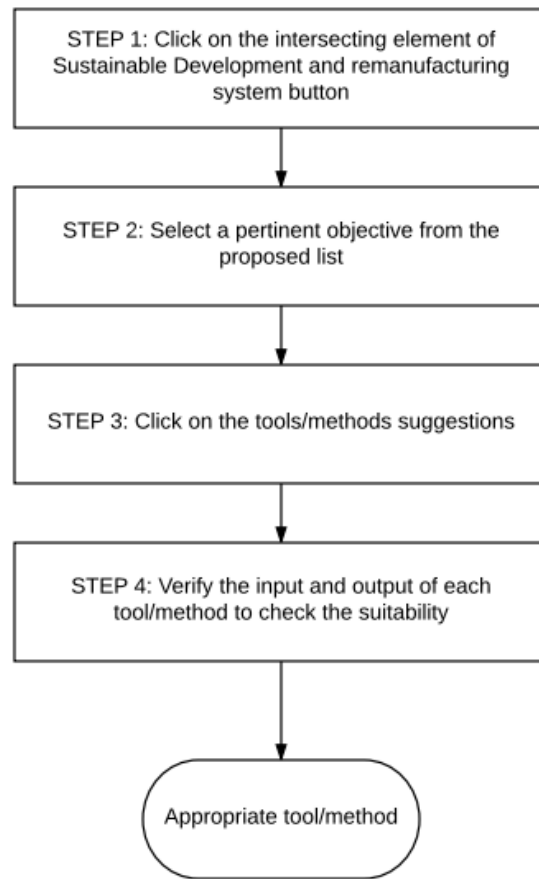


Figure 32: The Steps for the Choosing Method

ii. Interface for the Classification Method

There are many existing DfRem tools and methods, and there are also invention to create new to facilitate design and planning process. For a pertinent and updated database, it is important to ensure that the configurator is easy to be updated with new tools/methods. The second function of this configurator is used as an interface for user to key in the input for the classification method (list of inputs and outputs of an analysed tool/method). These inputs are then analysed manually by the user using the established rules as explained in the previous chapter. The keyed-in information can also contribute to the analysis and database of the choosing method as they are interdependent. The increase in the number of analysed DfRem tool/method could lead to the abundance of choice as well as the increase in the efficiency to handle users' needs and choices.

4.7. Function and Application

4.7.1. Functions

For a general overview, Figure 34 shows the proposed methods and configurator, their interdependencies, and their contacts with users using IPO (input, process, and output) model (Figure 33). The IPO model is used to better present inputs, outputs, and function of every components of this study where the single function of a component is well-detected.

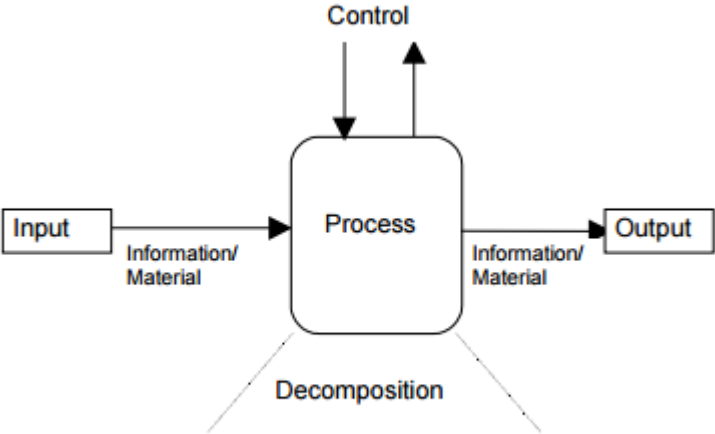


Figure 2.16: Traditional IPO process model

Figure 33: Traditional IPO Model by Carlson (1997)

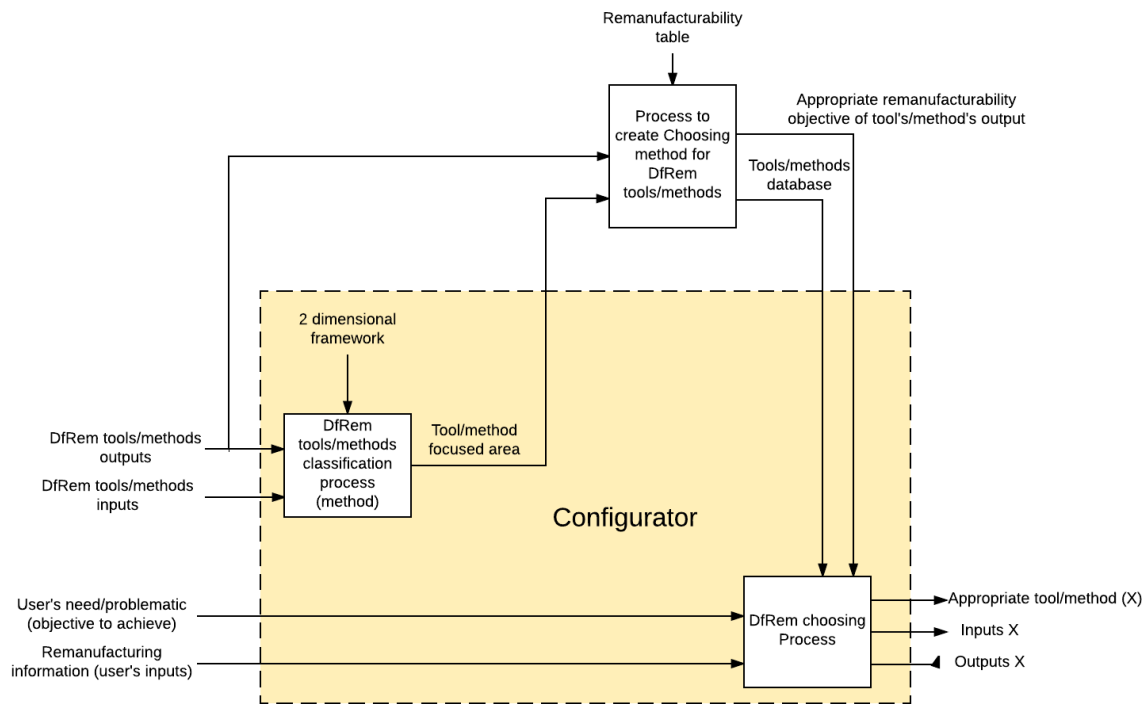


Figure 34: The IPO Model for the Proposed Methods and Configurator

The following are the end results that consist of three main components including their functions:

a. The classification method:

This method consists of individual tool analysis table and two-dimensional analysis grid. The inputs of this method are inputs and outputs of the analysed tool/method. This method emphasizes the nature of the analysed tool/method as the output.

b. The creation of choosing method:

This process utilises the remanufacturability table from proposition 1 as the framework. The inputs of this process are Information from the classification method and the output(s) of the analysed tools/methods. This process locates the outputs of tools/methods in the appropriate remanufacturability characteristic as the remanufacturability objective. Other than the remanufacturability objective, this process generates a database that contains the analysed tools/methods arranged in the remanufacturability table. This database is then used to create the choosing method configurator in (c).

- c. The configurator of the choosing method:

This configurator serves as an interface for users to use the previous methods. The users can use the two parts separately. The first part is the main part that is used to configure an appropriate tool/method according to users' need(s). This part requires users' need(s) and remanufacturing information as the inputs, and users will obtain appropriate tool(s)/method(s) suggestion along with its/their list of inputs and outputs. The second part requires users to key in the inputs and outputs of new analysed tool/method in the individual tool analysis table for the classification method. This action is for analysis reason, but the analysis part is done manually using the explained rules. This second part applies the same function like classification method which contributes to other method and configurator.

4.7.2. Applications

In this section, the users' applications of the developed method and configurator are listed and explained especially the "secondary" functions which are not explained elsewhere in this dissertation.

- a. Choosing a needed tool/method

As mentioned in several previous sections, the main application of the developed method and configurator is to allow user to choose tool(s)/method(s) that he/she needed. Case studies will be presented in the following subchapter, whereas the real scenario is resolved to demonstrate this application.

- b. Classifying tool/method systematically

Basically, this is the application of the classification method through direct usage. User will follow the usage steps in the classification method to obtain tool/method classification from 2DFR.

- c. Verifying the nature of tool/method

This is the "indirect" application of the classification method involving user to verify a pre-defined tool/method. In the beginning, a tool/method can be pre-defined by using other method. Later, user can apply the classification method on the pre-defined tool for verification reason.

- d. Sequencing several tools/methods

Another application of the proposed methods and configurator is to allow designer/remanufacturer to sequence several useful tools/methods that will be applied in achieving one or several objectives. This function works by using the available inputs and outputs information. The idea is to create a chain of tools with the output of the previous tool becoming the inputs of the following tool. This function is more crucial in a case which involves a company that could not provide the required input of a tool. This case will lead to the application of other tool/method in order to obtain the required input as the output. Figure 35 below shows an example of tools/methods sequence.

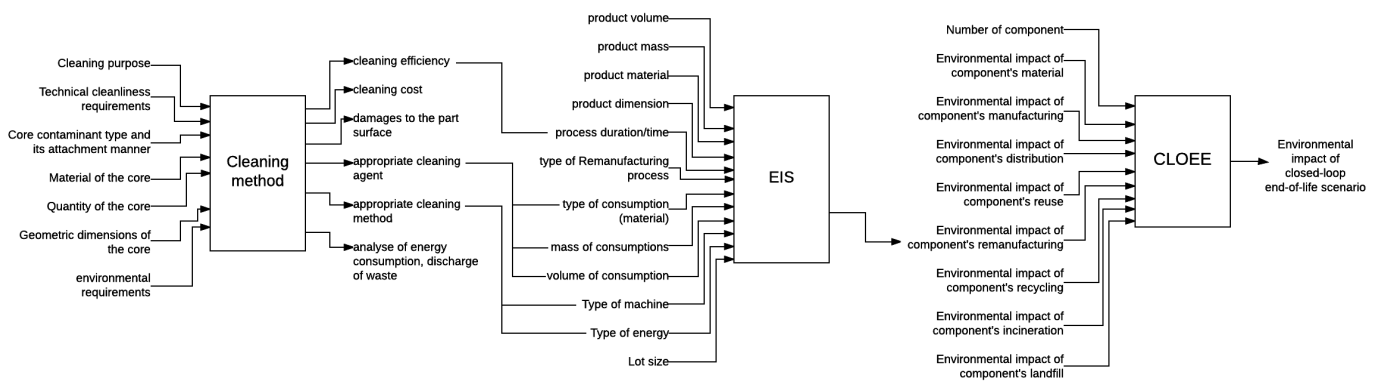


Figure 35: An input and output sequence of cleaning method, EIS tool and CLOEE tool

section, some illustrated study cases are created to demonstrate the application of the proposed methods and configurator. As shown in Figure 34, the final output that is destined for the user is the appropriate DfRem tool/method as well as the list of inputs and outputs. So, the main objective of this study case is to show how this method functions from the beginning until the end in specific given conditions. Since this study consists of several methods, there are also additional case studies that demonstrate the auxiliary functions.

Modelling scenario:

- Type of company: OEM
- Type of activity: mechanical product
- Experience in remanufacturing: 0-5 years
- Destination market: final
- Number of employee: more than 10
- Number of customer: more than 1

- Intensity of research and development activity: low to medium
- Reason for redesign: development and competition
- Description: After operating for more than 5 years, the decision maker has decided to adopt remanufacturing to reduce economic and environmental costs and increase company's good image for competitive reason. Their products' data are well-documented, and stakeholders are ready and agreed to implement the remanufacturing strategy economically and technically. The company is searching for tool/method that can suggest a wise operational and optimization moves to be implemented especially in planning remanufacturing operation and reverse supply chain.

For the first case study, the latest article by Matsumoto et al. (2016) is referred to identify the relevant remanufacturer's problem to date. From their study, the following are the barriers in remanufacturing:

- Effective collection of used product
- Development of efficient remanufacturing process (including efficient disassembly process and reverse logistics)
- Customer acceptance of remanufactured products

Using the information in the modelling scenario, we chose the "effective collection of used product" barrier as the user's problem in the first case study to demonstrate the application of the method and configurator. The step by step details are available in the next section.

The second case study is to demonstrate how tools'/methods' inputs and outputs function in deciding the appropriate tool(s)/method(s) when there are several suggestions of tools/methods. Since this method is still in the development phase, the objective of "high capacity performance level" from economic + remanufacturing operation is selected because it offers three tools/methods as suggestions. The detail for the steps and description is explained in 4.8.2.

4.8.1. First case study: An effective collection of used product

By utilising the information in the modelling scenario, remanufacturer intended to search academic tools/methods that will help the company in achieving an effective collection of used product. The word "effective" in the aimed objective is seen as adequate

to accomplish purpose from economic, environmental, social and technical perspectives. This is in line with the company's goal in being competitive. After applying the configurator and the steps in Figure 32, remanufacturers/designers in this case can start by clicking at the button to select their objective such as reverse supply chain + economic, environmental, social and technical button to select the aimed objective. The following are the possible results:

- a) Economic + reverse supply chain: Efficient and beneficial collection system
- b) Environmental + reverse supply chain: Optimum centre locations and capacities
- c) Social + reverse supply chain: NA
- d) Technical + reverse supply chain: Planned logistic network, easy to be transported

The above objectives are among the closest objectives with the aimed objective, which is the effective collection of used product, but there is no suitable objective from the social perspective.

The list of suggested tools/methods is available in each of the proposed objective. The exact output and the list of required inputs of a tool are also presented with the selected tool/method. With reference to the limited analysed tools/methods (12 analysed tools/methods), the following are the results:

- a) Economic + reverse supply chain:
 - Efficient and beneficial collection system → RNDM tool
- b) Environmental + reverse supply chain
 - Optimum centre locations and capacities → RNDM tool
- c) Technical + reverse supply chain
 - Planned logistic network → RNDM tool
 - Easy to be transported → NA (no proposition yet)

From the limited suggestion, this configurator proposed RNDM tool as a tool that can help the company to achieve an effective collection of used product. Figure 36 shows the outputs and inputs of RNDM tool that are presented by the configurator. The following is the full list:

- RNDM inputs: Number of remanufacturing centres, service point, capacity of remanufacturing centre, installation cost, return rate after inspection, material flow, remanufacturing cost, transportation cost, distance travelled, testing and inspection cost.

- RNDM outputs: number of remanufacturing centres required, amount of investment, which service point should be served from which remanufacturing centre, geographical location of manufacturing centres.

The screenshot shows a window titled "UserForm1" with a red close button in the top right corner. The form is divided into four sections:

- Objectif:** A dropdown menu with the selected option "Efficient & beneficial collection system".
- Outils disponibles:** A list box with "RNDM" selected and highlighted in blue.
- Implementation:** A text box containing the following text: "Number of remanufacturing centers, service point, capacity of reman center, installation cost, return rate after inspection, material flow, remanufacturing cost, transportation cost, distance traveled, testing and inspection cost".
- Outputs:** A text box containing a list of outputs: "-Number of remanufacturing centers required", "- Amount of investment", and "- Which service point should be served".

Figure 36: The Inputs and Outputs of the RNDM Tool Presented by the Configurator from Reverse Supply Chain + Economic Cell

This finding allows the company to shortlist the available tools/methods based on their objective. This method and configurator cut down the searching time and effort. The available inputs and outputs are given to allow users to analyse and consider if the suggested tool/method could fulfil the company's needs. If the suggested tool serves their needs, a further research on the tool/method can be done for a better understanding of the application process.

4.8.2. Second case study: High capacity performance level

Using the same information as the first study case, the second study case emphasizes a different objective, which is to achieve "high capacity performance level" from economic + remanufacturing operation perspectives. By applying the same steps as above, the configurator (see Figure 37) gives three available tools/methods such as the following:

a. Cleaning method:

- Inputs: Characteristic of damage (type, level, location, number), recovering process, failure rate for processing resources, number of remanufacturing process, machine cost and time for processing, tool cost for processing, ideal quality of remanufactured core.

- Outputs: Appropriate cleaning method, cleaning efficiency.

b. Reliability and cost optimization for remanufacturing process tool:

- Inputs: Number of damage, number of remanufacturing process operation, machine cost for processing a core per unit time, machine time for machine to finish the process, tool cost for processing a core per unit time, processing time, ideal quality of the remanufactured core, evaluated quality of the returned core.

- Outputs: Optimal (cost and reliability) sequence of remanufacturing operation.

c. R-DFLP tool:

- Inputs: Time duration (in days) of the period t ; number of the cores of type k in period t ; probability of the cores of type k being assigned to the r th processing routing in period t ; machine availability of the i th processing cell (hours/day); machine efficiency (in percentage) of the i th processing cell corresponding to machine failures; average processing time (in minutes) for the cores of type k in the i th processing cell, length of the machines in the i th processing cell ($M_{li} \geq M_{wi}$); width of the machines in the i th processing cell, length of the remanufacturing facility ($S_l \geq S_w$); width of the remanufacturing facility; the width of main road designed in the facility; relocation cost for the machines in the i th processing cell; material handling cost of cores of type k per unit of distances, relocation budget in period t ; number of processing cell, number of rows.

- Outputs: Optimal (cost and efficiency) remanufacturing facility layout scheme.

The screenshot shows a window titled "UserForm1" with a close button in the top right corner. The main content area is divided into four sections:

- Objectif:** A dropdown menu currently showing "High capacity performance level".
- Outils disponibles:** A list of three items: "Cleaning Method" (highlighted in blue), "Reliability and cost optimisation for remanufacturing process", and "R-DFLP".
- Implementations:** A text box containing the following text: "Characteristic of damage (type, level, location,number), recovering process, failure rate for processing resources, number of reman process, machine cost & time for processing, tool cost for processing, ideal quality of remanufactured core".
- Outputs:** A text box containing two bullet points: "- Appropriate cleaning method" and "- Cleaning efficiency".

Figure 37: The List of Tools/Methods for “High Capacity Performance Level” Objective in Economic + Remanufacturing Operation Cell

From the above information, the outputs of the three tools/methods are the outputs that the company might be interested. The cleaning method is expected to give solution on appropriate cleaning method and cleaning efficiency, the reliability and cost optimization for remanufacturing process tool is expected to propose an optimal remanufacturing operation sequence, and the R-DFLP tool is expected to suggest an optimal remanufacturing facility layout scheme. These outputs are useful for the company to plan their remanufacturing operation for the first time. However, the inputs parameters which are required for each tool/method are not entirely suitable for this company.

The inputs for the R-DFLP tool tend to be used for the relocation activity, which are not very relevant for a first approach. Referring to reliability and cost optimization for remanufacturing process tool, it is difficult to provide the required consistent data (e.g., machine cost for processing a core per unit time, average processing time) if the company runs the remanufacturing activity for the first time. The most that the company can do is to provide experiment information; however, there is the risk of giving inaccurate data when running the real activity. After considering these reasons, the only appropriate tool/method for this company is the cleaning method.

4.9. Conclusion of Chapter Proposition 2

Results related to the “Remanufacturing tool/method” survey

From the above research, some issues can be discussed before reaching a conclusion. Start with the results of the survey at the ERN workshop in 4.1, the remark on the rare usage of the existing specific remanufacturing tools may be due to the several reasons stated by Hatcher et al. (2011) which are:

- The OEMs develop their own in-house methods and tools for remanufacturing activities especially for the operational tasks.
- The complexity of the academic designed tools as many of these tools are in the form of mathematical models and software tools/methodologies
- The fact that most of these tools/methodologies are only suitable for late applications in the design process, when most major decisions have already been made.
- Remanufacturers prefer using the existing design approach concepts which is considered relevant to the enhancement of remanufacturability since it is easier to understand and more familiar to be used.

One possible reason that had not been mentioned by Hatcher et al. is that the remanufacturing tools/methods developed by the academician are not all tested in the industry. Therefore, the relevancy issue on the introduced concept and data might be questioned by some users. This reason might also become a concern to the developed methods and configurator in this chapter, which are used or made up with the existing remanufacturing tools/methods. Although the peer review process attempts to ensure the scientific validity of academic tools/methods, the fact that these tools/methods were developed as new and immature theories, unproven industrially and still in progress study are somehow appeared to cast doubt on their relevance. In addition, some of the developed academic tools/methods are using contradictory principles. A situation that can be imagined is when the configurator proposed two or three tools/methods with a contradictory principle to achieve an objective. User might confuse on which tools/methods to chose and which principle is more accurate. A further study with more focus on this issue is therefore suggested.

Classification method

Moving to the discussion on the developed method, the individual tool analysis of the classification method requires a step for the analysis of the input and output parameters in

order to classify them. This step demands user to give a 1, 0.5 or no score to every analysed parameter based on the definition of every element. This step depends greatly on the user which might produce different results due to the different interpretation between users especially for the indirectly related parameter such as “cleanliness requirement”. This parameter is strongly related to the technical element. But, it can be related to the economic element as the more stringent requirement might increase the cost, and also might need extra skill from employees (social element). This “extra” relation can vary based on user’s exposure and interpretation of the method. To minimize the human intervention to the final result, automated analysis might be the solution.

To sum up, this chapter presents several contributions such as the following:

- A method to identify and classify DfRem tools/methods.
- A method to choose Dfrem tools/methods.
- A configurator for the developed method as users’ interface.
- The overview of the existing DfRem tools/methods from the superposed output parameter.
- The list of functions and applications of the developed methods and configurator.
- Two case studies to demonstrate the usage of the developed methods and configurator in real situation.

Chapter 5: Conclusion and Perspectives

5.1. Conclusion

This work contributes to the integration of sustainable development aspects in remanufacturing system. The aim of this work is to facilitate designer to design remanufactured product for sustainable development with the following focus:

- Characterising remanufactured product and process for sustainable development.
- Proposing method to classify and choose DfRem tools/methods from both remanufacturing system and sustainable development perspectives.

A literature review on remanufacturing process shows that it does not represent remanufacturing activity as a whole since it only presents the internal process that happened in the remanufacturing centre. Therefore, a wider perspective of remanufacturing is chosen from the study of remanufacturing system by Barquet et al. (2013). On the other hand, the definition of sustainable development by Fatimah et al. (2013) that integrates technical aspect is also chosen. This is relevant as the technical aspect plays a big role in remanufacturing decision making. A framework called 2DFR is developed by using these two perspectives. It differs from other previous studies where characterization is only seen from a single perspective view. This framework is used to establish the characterization of product and process remanufacturability. The retained characteristics are presented in a table and serve as a guideline for designers and decision makers in designing remanufactured product for sustainable development. This study had gathered feedbacks from designers and remanufacturers during a remanufacturing workshop in order to validate the element of 2DFR and the content of remanufacturability characteristics. Surveys were conducted to investigate users' point of view on the relevancy and the applicability of the developed concepts and details. The overall feedbacks were positive with some remarks and suggestion for improvement.

The second emphasized area of this study is on remanufacturing tools and methods. Remanufacturing tools and methods has become a common research trend nowadays. It is an indicator of a well-established foundation of basic remanufacturing knowledge where academician started to think for its optimization through tools and methods. Research on tools and methods aimed to facilitate users in various applications. In this dissertation, a

tool/method is seen as one knowledge expertise. Therefore, the 2DFR is used to create a method to classify the numerous existing tools/methods.

An application was developed, using the classification method and the previous remanufacturability table, with the objective to help designer to use an appropriate tool/method based on his/her need and problem. Twelve existing tools and methods were analysed to test the classification method and become the database for the proposed application. In order to validate these works, two illustrated case studies were created to test the function and to demonstrate the application.

The following are some remarks regarding the developed work:

- The ability of a product to be remanufactured (remanufacturability) must be regarded from the early stage of product design. From sustainable development perspective, this ability must also consider the constraint on each stages of remanufacturing system. Specific product characteristics that ensure remanufacturability of a product could provide direct and easy-to-use information. It can be used as guidelines and check-list for designers and decision makers during design and decision making phases.
- It is not always the case, for a remanufacturing activity, to offer benefits. A misleading product strategy, poor remanufacturing planning, and an ill-manage operation will normally lead to loss. Product research, guideline, and pre-assess tools and methods are able to minimize the risk of loss.
- Many academic studies were done on tools and approaches that might be able to optimize remanufacturing activities. Even though this study only presented twelve tools/methods, it does not represent the reality of this domain. Unfortunately, it is rare to see the application of the mentioned tools/methods in the real industry. This might be due to the difficulty to gain access to these tools/methods besides understanding and applying them especially without a competent instructor. Serious effort has to be done to increase accessibility and applicability of these tools/methods in the industry.

5.2. Perspectives

In this dissertation, the focus was on the design for remanufacturing and the use of remanufacturing tools and methods to achieve sustainable remanufactured products. It is an ambitious objective to assist designers and remanufacturers in the early phase of their remanufacturing activity by providing a new framework and remanufacturability characteristics. But, this study aims at facilitating the early design and decision making process with the configurator that will be soon able to provide good advices on the methods and tools to apply. Nevertheless, some perspectives have to be drawn:

- a. For the 2DFR framework and remanufacturability characteristics, more analysis and research are needed:
 - The validation of this framework has to be done to improve the list of industrial processes. This was highlighted during the short introduction workshop that was conducted in the framework of the ERN project. Feedbacks from companies engaged in this network would be of great interest to finalise the 2DFR framework.
 - A further study could be done on the prioritization issue focusing on a case where all the ideal aspects cannot be achieved. A generic prioritization flow chart is an exemplary proposition that might help companies.
- b. Regarding the methods and configurators for remanufacturing tools and methods, the following are the possible perspectives:
 - To add-up the database of methods with the existing remanufacturing tools and methods to obtain a more pertinent tool.
 - To ensure that industrial designers and remanufacturers could test and validate the developed methods. Remarks and feedbacks will be considered to enhance the developed methods.
 - To upgrade the user's manual analysis in the classification method into an automatic analysis for a standardize classification. The actual classification method depends hugely on users to define the inputs and outputs of a tool/method. An automatic analysis will minimize the influence of the users in defining the analysed inputs/outputs as well as generating a homogeneous and standard result.

- To develop the sequencing function of the tools/methods since it is not well-developed in this study. It is also beneficial to develop a more user-friendly interface for this function.

In fact, the contribution of all the stakeholders and researchers is needed to complete this work along the next years and following the future remanufacturing developments. But the fact that a european network about remanufacturing is becoming true will certainly favor those contributions for sustainable remanufacturing.

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Annex

Annex A. Remanufacturability tables (with references)

a. Remanufacturability from economic perspective

4 Pillars SD	6 Aspects of Rem System	Characteristics	References	Implementation (Product or Process)
Economic	Design for reman (product)	Minimum operating time	Author's opinion	Product form, type, and number of fastener, material, production type, product's cost
		Mass-production	Shu and Flower (1993)	
		High (critical) material recovery	Lopez Ontiveros (2004)	
		Less material/component used	Gallo, Romano, & Santillo, 2012	
		Minimum cost	Gallo, Romano, & Santillo, 2012	
	Reverse supply chain	Minimum transport cost	Ferrer & Clay Whybark (2000)	Product/packaging/storage characteristic (Ferrer & Clay Whybark, 2000), optimum lot size, stock size, transport type/capacity/cost , type of fuel, customer demand, machine capacity, trajectory planning, centre locations cost and capacities (Subramoniam et al, 2009; Kizilboga et al., 2013), relationship between supplier and remanufacturer (Ostlin, 2008), merge with direct supply chain, buy back cost, return and demand rates, distance, Product features, pre-assess activity, Labor Management and Workforce Flexibility, Proactive Transportation
		Minimum storage cost,	Ferrer & Clay Whybark (2000)	
		Minimum packaging cost	Ferrer & Clay Whybark (2000)	
		Short RSC channel	Barquet et al., (2013)	
		Efficient & beneficial collection system	Subramoniam et al. (2009) Kizilboga et al. (2013)	

		High return rates and demand rates	ERN workshop	Management, Secondary Market Strategies, Consumer and Market Engagement (Adamson, 2016)
		Possible to pre-assess	ERN workshop	
	Information flow in reman system	Minimum cost	Gallo, Romano, & Santillo, 2012	Tracking method/device (Ferrer & Clay Whybark, 2000), collaboration (Barquet et al.,2013; Lindkvist and Sundin, 2013), communication (Barquet et al.,2013; Lindkvist and Sundin, 2013), Material flow, return and demands rate, forecasting
		Reduce uncertainty in the timing and quantity of returns and demand	Barquet et al., 2013	
	Employee knowledge and skill	Maximum profit,	Author's opinion	Number and type of employee, employee's salary, location, training and formation (Barquet et al., 2013)
		Minimum cost,	Art Diamond & Morgenstern, 2007	
		long-term investment on employee	Ferrer & Clay Whybark, 2000; Liu et al., 2013; Barquet et al., 2013, Jacobsson, 2000	
	Reman operation	Process cost < new product cost	Shu and Flower, 1993; Lopez Ontiveros, 2004	Product characteristic (Gamage et al.,2013) , lean remanufacturing process (energy, time) (Hammond et al., 1998; Gamage et al., 2013), remanufacturing cost (Atasu et al.,2010) , type and amount of consumption, lot size
	Commercialization reman product	Remanufactured product price < new product price,	Lopez Ontiveros, 2004	Product price (Atasu et al., 2010), market demand, government policy (Webster and Mitra, 2007) , transfer pricing (Toktay & Wei, 2011), direct competitors, maximize market share of remanufactured product, market studies (Atasu et al., 2010, Market segment
		Redemption Price < remanufactured product price,	Lopez Ontiveros, 2004	
		High demand, minimum cannibalization	Toktay and Wei, 2011	
		Price that convinced customers	ERN workshop	
		Systematic	Author's opinion	
		Effective	Author's opinion	

b. Remanufacturability from environmental perspective

4 Pillars SD	6 Aspects Rem System	Characteristics	References	Implementation (Product or Process)
Environmental	Design for reman (product)	High material recovery	Lopez Ontiveros, 2004	Material (type, mass) (Lopez Ontiveros, 2004; Luttrupp & Lagerstedt, 2006), remanufacturing process, Product features (Luttrupp & Lagerstedt, 2006) , pre-assess activity, LCA, treating toxic substances (Luttrupp & Lagerstedt, 2006).
		High saved energy and material	Lopez Ontiveros, 2004; Luttrupp & Lagerstedt, 2006	
		Minimum env impact in usage phase	Luttrupp & Lagerstedt, 2006	
		No toxic substances (REACH compliance)	Art Diamond & Morgenstern, 2007	
		Possible to pre-assess/ assess environmental impact	ERN workshop	
	Reverse supply chain	Minimum pollution from product and process (REACH compliance)	Ferrer & Clay Whybark, 2000	Product's characteristics (Ferrer & Clay Whybark, 2000), Energy used, stock size, type of transport, type of fuel, Centre location and capacities (Kizilboga et al., 2013), distance, Product features, pre-assess activity, LCA (ERN workshop)
		high energy saving	Lopez Ontiveros, 2004; Luttrupp & Lagerstedt, 2006	
		Optimum centre locations and capacities	Kizilboga et al. (2013)	
		Possible to pre-assess/ assess environmental impact	ERN workshop	
	Information flow in reman system	Minimum environmental impact	Author's opinion	Tracking method/device (Ferrer & Clay Whybark, 2000), collaboration (Barquet et al.,2013; Lindkvist et al.,2013), communication (Barquet et al.,2013;

				Lindkvist et al.,2013)	
	Employee knowledge n skill	Well-educated and well-guided employee on environmental issue	Author's opinion	Employees' profile, training and formation	
	Reman operation	The entire reman process should result in a decrease in the total environmental impact	Gallo, Romano, & Santillo, 2012	Lean reman operation (energy, time), surface type, material, form/shape, component arrangement, cleaning procedure, cleaning agent, lot size	
		No toxic substances,	Art Diamond & Morgenstern, 2007	Work place, government policy (Art Diamond & Morgenstern, 2007), reman operation	
		Respect health & environment policy	Art Diamond & Morgenstern, 2007		
		Possible to pre-assess/ assess environmental impact	ERN workshop	Product features, pre-assess activity, LCA (ERN workshop)	
	Commercialization reman product	Well-educate and well-guided customer on environmental issue	Doshanov & Ahmad, 2015	Media, education	

c. Remanufacturabilites from social perspective

4 Pillars SD	6 Aspects Rem System	Characteristics	References	Implementation (product or process)
Social	Design for reman (product)	Specific expertise (easy future remanufacturing)	Ijomah et al., 2007	Designer's knowledge and motivation (Hatcher et al., 2013) , formation, visits, guideline, brainstorming, Contract of warranty, product quality, Intellectual property (John and Robert, 2009)
		High motivation	Hatcher et al., 2013	
		Possible to give warranty	Anityasari, 2008	
		Safe to be remanufactured (ownership issue)	John and Robert, 2009	
	Reverse supply chain	Encourage the client to return and bring the suppliers close to the remanufacturing company	Adamson, 2016	Contract (Ostlin, 2008) , return programme/management (Adamson, 2016),

		Respecting the rights of remanufacturers and customers	Author's opinion	promotion, guideline, management, awareness program
		Socially safe working environment	Branch, 2012; Fair, 2015	
	Information flow in reman system	Collaborating with suppliers and others in the chain,	Art Diamond & Morgenstern, 2007	Communication and cooperation (Stahel, 1995), training and formation, enforcement
		Good networking,	Stahel, 1995	
		Smooth communication	Author's opinion	
	Employees' knowledge and skill	Well trained employee	Author's opinion	Worker's profile, human resource management, training,
		High level of consciousness	Fair, 2015	
		Specific task for specific workers skill level	Author's opinion	
		Attractive task (job satisfaction)	Fatimah et al., 2012	
	Reman operation	Socially safe working environment	Branch, 2012; Fair, 2015	Enforcement, housekeeping, Communication (ERN workshop)
		Stakeholders share and give feedback, suggestion	ERN workshop	
	Commercialization reman product	Meet customer expectation,	Adamson, 2016	Customer's satisfaction, product and company's image, promotion, education, marketing program, services, contract, environmental impact communication, local business communication, Contract, management, warranty, information, Patent of reman process, PSS business model
		Good image	Adamson, 2016	
		Interesting and convincing	Adamson, 2016	
		Respecting the rights of remanufacturers and customers	Author's opinion	
Consumer trust in reman product = new		ERN workshop		

d. Remanufacturabilites from technical perspective

4 Pillars SD	6 Aspects Rem System	Characteristics	References	Implementation (Product or Process)
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Technical	Design for reman (Product)	Have a core	Statham, 2006; Lund, 1984	Design, reuse cycle, usage condition, product lifetime (first, total)
		Cannot be consumed in its use	Lund, 1984	
		Original function of the product and its level of performance can be restored by remanufacturing	Statham, 2006; Lund, 1984	
		Not/slightly change over the years	Statham, 2006	Technology cycle, product lifetime (first, total)
		Slowly evolving technology	McConocha & Speh, 1991	
		Long useful life	Lund, 1984; Lopez Ontiveros, 2004	Material, form, manufacturing quality, fastening method
		Hardly damaged	Ijomah et al., 2007	
		Corrosion resistant	Amezquita et al., 1995	
		Modular component, fastener, interface	Lopez Ontiveros, 2004	Material, fastening methods, product structure (dimension, form), internal arrangement
		Standardisable component	Amezquita et al., 1995	
		Integration of several stakeholders constraints	ERN workshop	Networking (ERN workshop), integrated design (ERN workshop)
	Reverse supply chain	Planned logistic network,	Barquet et al., 2013	Logistic network, merge with direct supply chain
		Determine the safety stock levels and the length of the planning horizons	Ferrer, 2008	
		Easy to be transported	Author's opinion	Transport and storing system (container), stock size, type of transport, schedule, distance
		Aggregate parts early to avoid transporting useless item	Author's opinion	
		Enough storage space	Stahel, 1995	
		Good storage	Stahel, 1995	

	Easy supply of spare parts	ERN workshop	Additive manufacturing (ERN workshop)
	Ensure core supply	ERN workshop	PSS business model (ERN workshop); pay back (ERN workshop)
	Select core for reman before they are considered as waste	Author's opinion	
Information flow in reman system	Easy and early determination of component condition (traceable)	Author's opinion	Information system, tracking device (Ferrer & Clay Whybark, 2000) , forecasting, material flow
	Allow feedback to be routed back	Ferrer, 2008	
	Good control/coordinate of information	Lindkvist, 2013; Barquet et al., 2013	
	Accurate information	Barquet et al., 2013	
	Long term product data management	ERN workshop	
	All stakeholders have access on product information	ERN workshop	Networking (ERN workshop)
Employee knowledge n skill	Transferrable knowledge and skill	Author's opinion	Standardize and documented operation and guidelines, apprentice, Collaborate with other stakeholders
reman operation	Easy to disassemble	Amezquita et al., 199	Number of components, fastening method, disassembly force exertion, tool requirement, positioning and accessibility (Soh et al., 2014), connectivity complexity, DfD guidelines and instructions (Dowie and Simon, 1994)
	Allow complete disassembly	Lund, 1984	
	Allow non-destructive disassembly	Soh et al., 2014	
	Efficient disassembly process	Author's opinion	
	Minimum disassembly time	Soh et al., 2014; Amezquita et al., 1995; Lacerda, 2004	
	Minimum number of fastener	Author's opinion	
	Easy to be cleaned	Liu et al., 2013	Number of components, surface type (Liu, 2013), material (Liu, 2013), form/shape, component
	Minimum cleaning time	Lacerda, 2004	

		Material with higher melting point	Author's opinion	arrangement, cleaning procedures (Liu, 2013), cleaning agent (Liu, 2013), lot size, cleaning purpose (Liu, 2013)
		Minimum variety of material	Author's opinion	
		Similar and efficient cleaning procedures and cleaning agents	Author's opinion	
		Wear resistant	Ijomah et al., 2007	
		Corrosion resistant	Amezquita et al., 1995	
		Good cleaning quality	Liu et al., 2013	
		Easy to sort/inspect	Errington and Childe, 2013	Component's name, component's function, signature features (face types, dimensions, diameter/length ratio)
		Minimum time	Lacerda, 2004	
		Easy access	Author's opinion	Part accessibility, Fastener accessibility
		Capable of being replaced easily	Statham, 2006	Part material and fastening methods, machine
		Prevent damage during part insertion	Author's opinion	
		Minimum replacement time	Lacerda, 2004	
		Minimum function for every component	Author's opinion	
		Bulkier parts (more material) to allow rework	Author's opinion	
		Easy supply of spare parts	ERN workshop	Additive manufacturing (ERN workshop)
		Easy to reassemble	Lacerda, 2004	Number of components, tolerance
		Minimum reassembly time	Lacerda, 2004	
		Easy to be handled	Author's opinion	Form/shape, number of components, tools
		Easy identification	Errington and Childe, 2013	Material, component arrangement, test procedure
		Mirroring reassembly order	Author's opinion	
Standardize test procedures	Lacerda, 2004			

		Mapped	Author's opinion	Lean remanufacturing operation (time, machine, material, lot size, energy)
		Formalize operation	Author's opinion	
	Commercialization reman product	Easy to manage	Author's opinion	Marketing system

**Annex B. Worksheet of remanufacturing workshop in Grenoble ERN
networking event**

Workshop Agenda

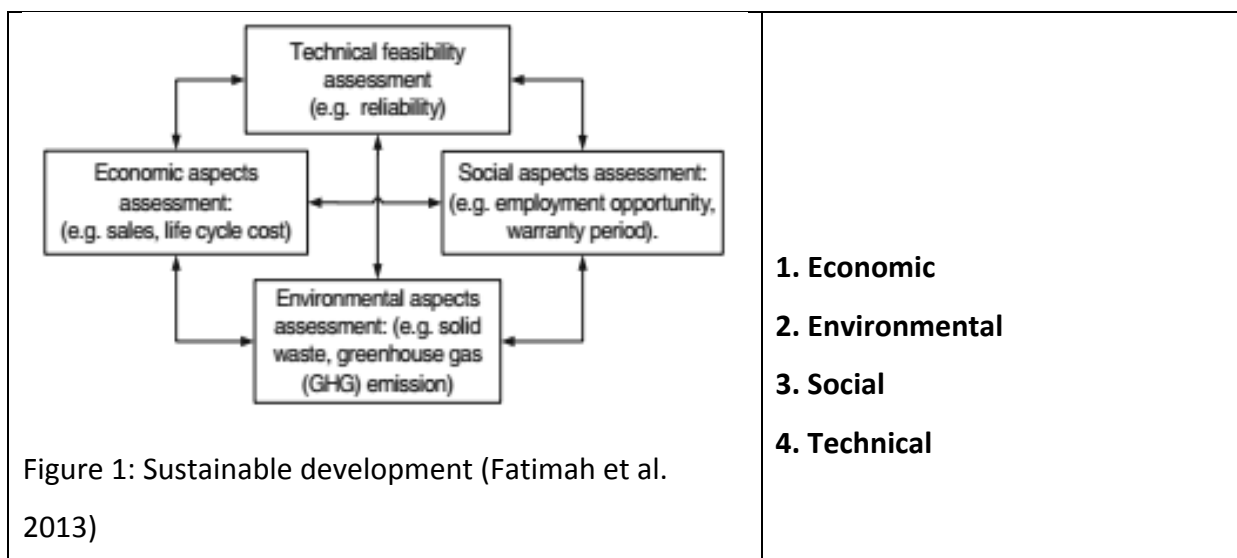
10 min: Introduction

50 min: Filling out workshop work sheet

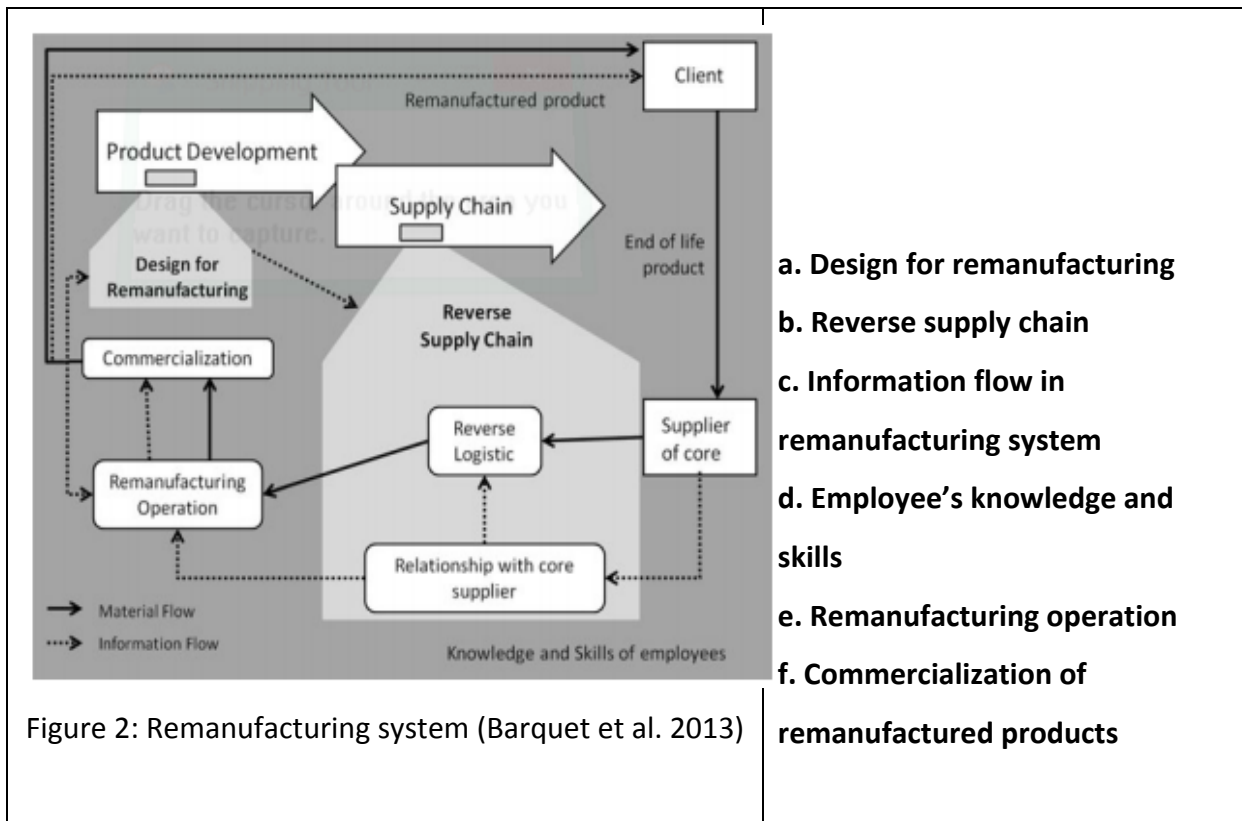
20 min: Discussion and restitution

Introduction: A two-dimensional remanufacturing framework

First dimension: Sustainable Development (Fatimah et al. 2013)



Second dimension: Remanufacturing System (Barquet et al. 2013)



Remanufacturability matrix

In the table below, choose at least 4 cells that normally address remanufacturing concerns in your activities and rank them regarding their emphasis (1 very important, 5 for less important)

	1. Economic	2. Environmental	3. Social	4. Technical
a. Design for remanufacturing	1a	2a	3a	4a
b. Reverse supply chain	1b	2b	3b	4b
c. Information flow in remanufacturing system	1c	2c	3c	4c
d. Employee's knowledge and skills	1d	2d	3d	4d

e. Remanufacturing operation	1e	2e	3e	4e
f. Commercialization of remanufacturing product	1f	2f	3f	4f

For those concerns please look at the corresponding cells in the table provided in the annex. Check with the announced theoretical objectives and add those of your company if missing. Check with the implementation means and add those of your company if missing.

	Your company objective	Your implementation
Concern 1: Cell ..		
	Your company objective	Your implementation
Concern 2: Cell ..		

Concern 3: Cell ..		
Concern 4: Cell ..		

Remanufacturing Tools

Fill in the table with remanufacturing tools or methodologies used within your company:

	1. Economic	2. Environmental	3. Social	4. Technical
a. Design for remanufacturing	1a	2a	3a	4a
b. Reverse supply chain	1b	2b	3b	4b
c. Information flow in remanufacturing system	1c	2c	3c	4c
d. Employee's knowledge and skills	1d	2d	3d	4d
e. Remanufacturing operation	1e	2e	3e	4e
f. Commercialization of remanufacturing product	1f	2f	3f	4f

Specify for each of those tools if they are used for strategic or operational purposes

For which concerns do you think there is a lack of remanufacturing tools?

Please detail you needs.

From your opinion, what are the important characteristics that remanufacturing tool must have.

- i. _____
- ii. _____
- iii. _____
- iv. _____
- v. _____

Information regarding your remanufacturing activities:

What is your position?

Academic:

Professor/Expert Researcher Student

Professional:

OEM Independent remanufacturer

Third party remanufacturer Consultant

Other: _____

If you are from industry, in which business sector(s) is your company active?

Aerospace Automotive Consumer goods

(Office) Furniture

Heavy duty and off road equipment

Machinery

Marine industry

Medical equipment

Rail industry

Other: _____

What is your company's activity?

Services

Products

Other: _____

How many years have you been working in remanufacturing?

Zero

Less than 2 year

2 to 5 years

5-10 years

More than 10 years

Thank you for your participation!

Annex C. Results for the analysed tools/methods from the two-dimensional analysis grid

a. Recore

	Recore Input						Recore Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic		1					1	1	1			
2. Environment												
3. Social							1	1	1			
4. Technical		1	1				1	1	1			

Table B-a: Analysis grid for Recore input and output

b. RNDM

	RNDM Input						RNDM Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic		1	1	1	1		1	1		1		
2. Environment							1	1		1		
3. Social							1	1		1		
4. Technical		1	1	1	1		1	1		1		

Table B-b: Analysis grid for RNDM input and output

c. Cleaning Method

	Cleaning method Input						Cleaning method Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic										1		
2. Environment										1		
3. Social												
4. Technical			1		1					1		

Table B-c: Analysis grid for Cleaning method input and output

d. Environmental impact Simulator (EIS)

	EIS Input						EIS Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic												
2. Environment								1		1		
3. Social												
4. Technical	1		1		1							

Table B-d: Analysis grid for EIS input and output

e. Modular Grouping Explorer (MGE)

	MGE Input						MGE Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic			1				1		1		1	
2. Environment							1		1		1	
3. Social												
4. Technical	1		1				1		1		1	

Table B-e: Analysis grid for MGE input and output

f. Design for Product Taken-Back Parts Reuse (DfTPR)

	DfTPR Input						DfTPR Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic							1		1			
2. Environment							1		1			
3. Social												
4. Technical	1		1				1		1		1	

Table B-f: Analysis grid for DfTPR input and output

g. Rempro Matrix

	Rempro Input						Rempro Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic												
2. Environment												
3. Social												
4. Technical	1		1	1	1		1		1		1	

Table B-g: Analysis grid for Rempro matrix input and output

h. Metrics for Assessing Remanufacturability (MAR)

	MAR Input						MAR Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic												
2. Environment												
3. Social												
4. Technical			1		1				1		1	

Table B-h: Analysis grid for MAR input and output

i. Remanufacturability Assessment Metrics Based on Design (RAMBD)

	RAMBD Input						RAMBD Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic												
2. Environment												
3. Social												
4. Technical	1		1		1		1		1		1	

Table B-i: Analysis grid for MAR input and output

j. Reliability and Cost Optimisation for Reman Process (RCORP)

	RCORP Input						RCORP Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic								1		1		
2. Environment												
3. Social												
4. Technical			1		1			1		1		

Table B-j: Analysis grid for RCORP input and output

k. Remanufacturing Dynamic Facility Layout Problem (R-DFLP)

	R-DFLP Input						R-DFLP Output					
	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufacturing product
1. Economic								1		1		
2. Environment												
3. Social												
4. Technical			1		1			1		1		

Table B-k: Analysis grid for R-DFLP input and output

Résumé long en français

1. Introduction

1.1. Les enjeux environnementaux dans l'industrie manufacturière

Au cours de la révolution industrielle, les questions environnementales n'étaient pas abordées lors de la conception et de la fabrication des produits. Cependant, dans la dernière décennie, les questions environnementales sont devenues des préoccupations majeures pour l'industrie. Cela est dû à la consommation croissante, par les pays industrialisés et en développement, de ressources énergétiques et matérielles dans une économie dite linéaire (voir la figure 1) qui applique le principe «prenez, utiliser, jeter». L'économie linéaire utilise ainsi des ressources naturelles et rejette les produits sous forme de déchets dans des décharges ou des incinérateurs dès leur fin d'usage. Cela a abouti à des situations critiques au niveau des ressources, du changement climatique et pose le problème de la gestion des déchets : ce qui a conduit, devant l'urgence, de traiter ces «déchets» ailleurs. Poussées principalement par les réglementations gouvernementales et des comportements de consommateurs, de plus en plus d'entreprises ont reconsidéré leurs objectifs avec un regard plus écologique.

Beaucoup de concepts ont été introduits pour résoudre ce problème, comme la « Pensée cycle de vie », le Design for Environment (DfE), l'Environmentally Conscious Manufacturing (ECM), le Cradle to Cradle, et l'éco-efficacité. En Europe, la Commission européenne a décidé d'encourager le concept de l'économie circulaire dont l'objectif est de maintenir la valeur des produits, des matériaux et des ressources dans l'économie aussi longtemps que possible et de réduire au minimum les déchets. Cette nouvelle dynamique a permis d'encourager les approches existantes comme l'écologie industrielle ou les approches du berceau au berceau, pour se passer du modèle de production linéaire.



Figure 1: L'économie linéaire (source: Henry, 2016)

1.2. Economie circulaire

L'économie circulaire est " quelque chose qui restore et régénère par la conception, et qui a pour but de garder les produits, les composants et les matériels dans ses niveaux d'utilités le plus élevés à tout moment, à la fois au niveau des cycles techniques et des cycles biologiques" (Ellen MacArthur Foundation, 2015"). Le cycle technique est défini par le management des stocks de matériaux qui sont finis. Les matériaux techniques sont récupérés et puis réintroduits dans un autre cycle technique. Le cycle biologique, quant à lui,

comprend les flux des matières renouvelables. Les nutriments renouvelables sont principalement régénérés dans le cycle biologique. Ceci est une alternative viable pour l'ancienne économie linéaire et repose sur trois principes:

- Préserver et valoriser le capital naturel
- Optimiser le rendement des ressources
- Favoriser l'efficacité du système

L'économie circulaire devrait offrir des avantages tels que réduire les émissions annuelles totales de gaz à effet de serre, augmenter la croissance économique et la création d'emplois, stimuler la compétitivité et assurer la sécurité de l'approvisionnement des matières, construire la résilience économique et environnementale, tout en encourageant les innovations. L'adoption de l'économie circulaire en Europe commence par l'application de changements importants dans différents domaines d'action. Pour le domaine clé << fabrication >> le remanufacturing est spécifiquement indiqué pour :

- Fournir des incitations afin de stimuler la conception de produit à cycles de vie bouclés,
- Créer des processus de production innovants et efficaces.

Si ces objectifs sont atteints, l'objectif final de l'économie circulaire mentionnée en haut sera potentiellement atteint aussi.

1.3. Remanufacturing

Le Remanufacturing est l'une des options utilisées pour boucler le cycle de vie du produit. La British Standards Institution BS 8887-2 (2009) définit le remanufacturing comme le processus de "ramener un produit dans un état au moins aussi bon qu'un produit neuf aussi bien en termes de performances que de garanties".

Selon les stratégies décrites dans la figure 2, le remanufacturing est le seul processus qui assure le même niveau de qualité de produits, alors que dans le cas du recyclage, certains matériaux sont déclassés dans des qualités inférieures. De nombreux chercheurs ont démontré les avantages des produits remanufacturés par rapport à de nouveaux produits ou à des produits recyclés, surtout du point de vue économique et environnemental (Giuntini et Gaudette, 2003; W Kerr et al, 2001;. Lindahl et al., 2006;. Sutherland et al, 2008;. Kim et al, 2008). Les résultats des recherches montrent que les bénéfices du remanufacturing reposent sur les composants (remis en état et contrôlés) et le processus de démontage et de remontage complet, qui garantissent la qualité des produits remanufacturés.

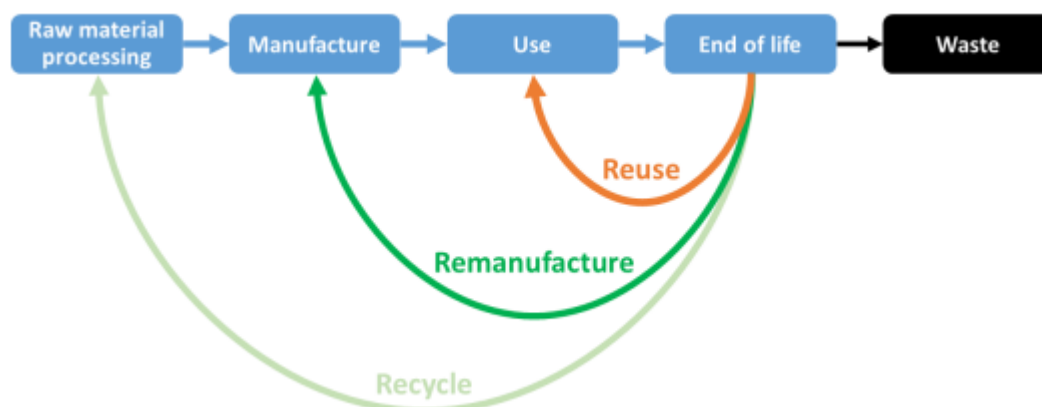


Figure 2: Les stratégies de cycle de vie en boucles fermées

Du point de vue de l'environnement, l'activité de remanufacturing est normalement prévue pour:

- Économiser de l'énergie
- Économiser la matière première
- Prolonger la vie des produits
- Éviter la mise en décharge
- Réduire la pollution

En outre, sur le plan économique et social, remanufacturing est considéré comme un modèle d'affaires qui peut satisfaire les besoins des consommateurs (produit de qualité avec un prix inférieur), créer de nouvelles possibilités d'emploi et de nouvelles parties prenantes, et construire une bonne image de l'entreprise. Après avoir listé ces avantages, l'un des défis les plus importants d'aujourd'hui pour le remanufacturing est d'assurer que le produit possède bien tous ces avantages quand il est réalisé. Ce défi est difficile à relever en raison de la complexité liés au produit lui-même, aux process de remanufacturing et aux incertitudes associées (quantité et qualité et délai des retours, durée de vie, ...). Un système de remanufacturing mal planifié et mal géré pourrait annuler les avantages attendus du remanufacturing.

1.4. La conception pour s'assurer un remanufacturing durable

Une activité de remanufacturing bien planifiée devrait commencer dès le début de la phase de conception du produit. Il est important de considérer la faisabilité du remanufacturing lors de la conception d'un produit car il peut contribuer à des avantages significatifs pour l'ensemble du processus de remanufacturing. Cet enjeu a conduit à de nombreuses recherches sur la conception pour le Remanufacturing (DfRem). Plusieurs études ont cherché à caractériser la relation entre des caractéristiques du produit et le succès de son remanufacturing. Il existe également de nombreux outils, méthodes et approches qui ont été développés pour aider les concepteurs et remanufactureurs à décider et planifier leur activité de remanufacturing. Cependant, la grande quantité d'outils / de méthodes utilisées pour le remanufacturing soulève le problème du choix des outils / méthodes. En effet, trouver le meilleur outil ou la meilleure méthode pour les besoins spécifiques d'une entreprise souhaitant participer au développement durable n'est pas évident. Nous avons pris le parti d'aider les concepteurs non pas par l'introduction d'un nouvel outil / d'une nouvelle méthode, mais avec la mise en œuvre d'une aide au choix d'outils / méthodes les plus appropriés parmi les outils / méthodes existants.

2. Les questions de recherche et le positionnement du travail

La première partie de la revue de la littérature fournit des informations sur les éléments du système de remanufacturing et le développement durable. Avec ces informations, cette étude vise à proposer un processus de planification et de prise de

décision en lien avec le remanufacturing. Il s'agit de guider les décideurs et concepteurs pour qu'ils intègrent le concept de développement durable ainsi que le système de remanufacturing en réponse à la première question de recherche qui est «comment caractériser les produits remanufacturés et le système de remanufacturing dans une perspective de développement durable? »

La deuxième partie de la revue de la littérature a porté sur les outils/ les méthodes de DfRem dans le domaine académique. ces outils/méthodes de DfRem sont dites peu utilisées par l'industrie (Hatcher et al., 2011). Cela peut être dû à plusieurs raisons dont l'une est la mauvaise gestion des informations telles que le manque d'outils / de méthodes de classification, le manque de bases de données de ces outils / méthodes, et le manque de revues critiques sur ces outils / méthodes. De ce fait, les concepteurs et remanufactureurs perdent un temps énorme et consacrent de nombreux efforts pour rechercher, analyser et choisir des outils / méthodes DfRem appropriées. Par conséquent, la deuxième question de recherche est "comment aider les concepteur à choisir les outils/méthodes de DfRem existants pour concevoir des produits remanufacturés dans un objectif de développement durable?" Ainsi, cette seconde proposition va se focaliser sur la gestion et le classement des outils/méthodes DfRem opérationnels.

La première question de recherche se concentre sur le cadre de travail : la définition et la caractérisation des produits remanufacturés pour le développement durable. Alors que la deuxième question de recherche est destiné à agir sur les outils/méthodes de DfRem et comment améliorer l'utilisation de ces outils / méthodes via une meilleure classification et gestion. La vue d'ensemble de cette thèse est présentée figure 3.

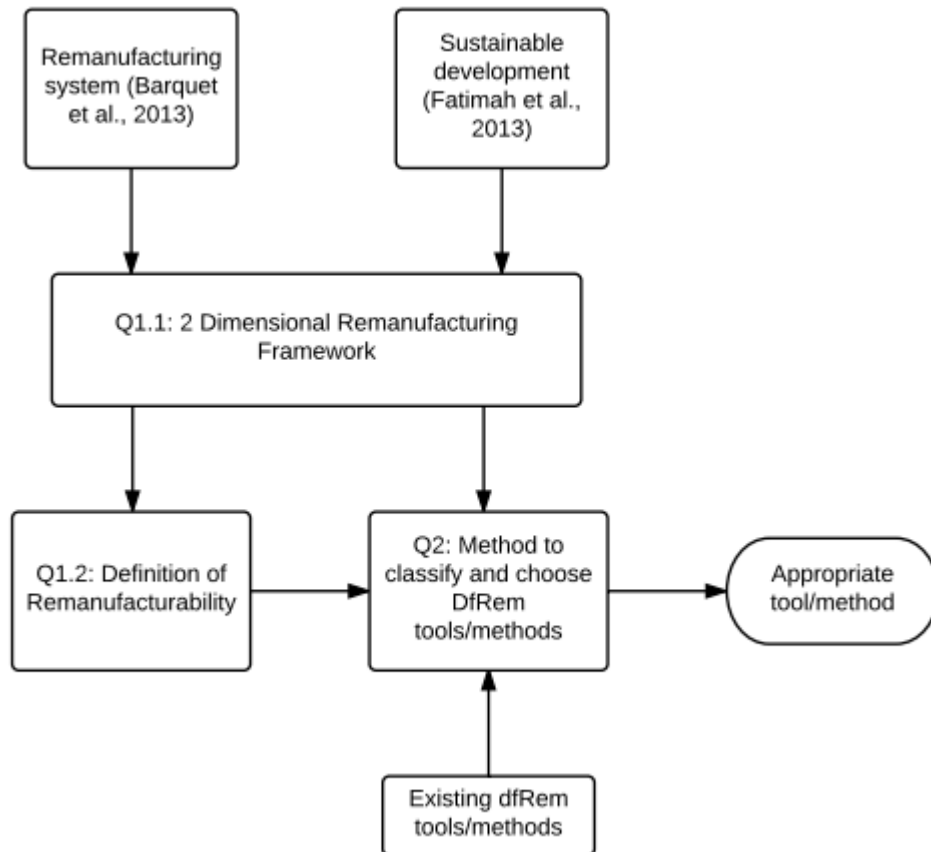


Figure 3: Vue d'ensemble des travaux de recherche

3. Proposition 1: Le Cadre du travail 2DFR : une cadre à 2 dimension pour le Remanufacturing et la Définition de la remanufacturabilité

La première proposition de cette thèse nous conduit à:

- Concevoir un cadre de travail intégré en prenant en compte les piliers du développement durable et le système de remanufacturing.
- Définir et caractériser la faisabilité de remanufacturing selon deux dimension : le développement durable et le système de remanufacturing

3.1 Le Cadre du travail à Deux Dimensions pour le Remanufacturing

La construction d'un cadre de travail à deux dimensions pour le remanufacturing (2DFR) a pour but d'intégrer les deux perspectives que sont le développement durable comme proposé par Fatimah et al. (2013) et le système de remanufacturing proposé par Barquet et al. (2013) en une seule perspective. Pour rendre le processus d'analyse et d'interprétation plus facile, nous avons créé un système qui fixe des éléments avec des

numéros et des lettres de l'alphabet. Commençons avec les éléments du développement durable comme ci-dessous:

- 1 pour l'aspect économique
- 2 pour l'aspect environnemental
- 3 pour l'aspect social
- 4 pour l'aspect technique

Suivi par les éléments du système de remanufacturing comme ci-dessous:

- A pour la conception de remanufacturing
- B pour la chaîne d'approvisionnement inverse
- C pour la circulation de l'information dans le système de remanufacturing
- D pour les connaissances et les compétences des employés
- E pour le process de remanufacturing
- F pour la commercialisation des produits remanufacturés

La vue intégrée a été réalisé avec l'aide d'un "tableau de 4x6" où les quatre éléments du développement durable sont disposés en lignes et les six éléments du système de remanufacturing sont disposés en colonnes (Voir tableau 1).

	a. Design for remanufacturing	b. Reverse supply chain	c. Information flow in remanufacturing system	d. Employees' knowledge & skills	e. Remanufacturing operation	f. Commercialization of remanufactured product
1. Economic	1a	1b	1c	1d	1e	1f
2. Environment	2a	2b	2c	2d	2e	2f
3. Social	3a	3b	3c	3d	3e	3f
4. Technical	4a	4b	4c	4d	4e	4f

Tableau 1: 4x6 Table

3.2 Remanufacturabilité du point de vue de 2DFR

Le mot remanufacturabilité a été utilisé dans cette thèse pour représenter les exigences de conception d'un produit qui sera remanufacturés. Ces exigences de remanufacturing devraient être implémentées dans chaque nouveau produit pour augmenter sa possibilité d'être remanufacturé. Le précédent concept permettant de raisonner selon deux dimensions, donne un nouveau regard sur la remanufacturabilité.

Même si les contenus sont semblables à ce que nous avons décrit précédemment dans la littérature, la description intégrée de chaque cellule est nécessaire pour aider le concepteur à l'utiliser. Par conséquent, chaque cellule a fait l'objet d'une explication afin de caractériser la remanufacturabilité selon les deux perspectives du cadre 2DFR.

3.3. Validation

Afin de valider cette proposition, nous avons mené une étude et recueilli des évaluations de concepteurs et de remanufactureurs sur la pertinence du concept de 2DFR et sur les définitions proposées de remanufacturabilité. Une enquête a ainsi été menée au cours d'un atelier spécifique mené durant un événement du réseau Européen ERN, qui s'est déroulé à Grenoble et qui a réuni des concepteurs, des consultants, des remanufactureurs (OEM et IR), et des académiques de plusieurs pays européens. Pendant l'atelier, chaque participant a reçu une feuille de travail avec les objectifs suivants:

- Introduire le 2DFR.
- Classer les problèmes de remanufacturing en utilisant le cadre 2DFR mis en place.
- Introduire et valider les objectifs théoriques et les moyens de mise en œuvre de la matrice de remanufacturabilité
- Enquêter sur les outils et les méthodologies de remanufacturing utilisées par les participants.
- Enquêter sur les opinions des participants sur les outils et méthodologies de remanufacturing.

4. Proposition 2: La méthode pour classer et Choisir les Outils / Méthodes de DfRem

Ce chapitre commence par les résultats de la deuxième partie de l'enquête précédente, qui s'intéressait aux «outils de remanufacturing». Cette partie de l'étude avait comme objectif de mettre en évidence l'importance d'une méthode pour aider à classer et choisir les outils/méthodes DfRem. Les réponses données par les participants soulignent que les outils et les méthodologies utilisées / suggérées par les participants sont majoritairement génériques. Peu d'outils spécifiques au remanufacturing sont effectivement appliqués dans l'industrie. Par conséquent, il y a un besoin fort de fournir une méthode qui aidera les parties prenantes du secteur du remanufacturing à trouver intelligemment des outils / méthodologies existantes et pertinentes.

Les outils / méthodes que nous avons inclus dans cette étude sont des outils/méthodes pour la prise en décisions opérationnelles ainsi que les outils/méthodes pour optimiser le processus de remanufacturing. 12 outils/méthodes avec différentes caractéristiques sont décrits ici et utilisés pour tester la compatibilité de la méthode proposé.

4.1. Classification d'Outils / Méthodes de DfRem (Ismail et al., 2014)

La première composante de la deuxième proposition est la méthodologie pour identifier et classer les outils / méthodes existants. Les 12 outils / méthodes sont classés à partir du point de vue du développement durable et du système de remanufacturing. Cette méthodologie utilise les périmètres d'entrée et de sortie des outils / méthodes analysées. Elle se compose de deux étapes d'analyse en utilisant deux types de tableaux, qui sont:

- l'analyse de l'outil individuel
- la grille d'analyse à deux dimensions

4.1.1. L'analyse de l'outil individuel

Le tableau d'analyse de l'Outil individuel a été créé pour analyser les paramètres d'entrée et de sortie d'un outil / d'une méthode selon les perspectives de développement durable et le système de remanufacturing. Après l'identification des paramètres d'entrée et de sortie, chaque paramètre a été analysé en lui donnant un score de contribution marqué dans la cellule appropriée. Les règles sont les suivantes:

- Une note de 1 est attribuée si le paramètre est directement lié aux deux éléments : développement durable et système de remanufacturing.
- Une note de 0,5 est donnée si le paramètre est indirectement lié à ces éléments.
- Pas d'évaluation si le paramètre n'est pas lié aux 2 éléments : développement durable et système de remanufacturing.

Ensuite, une note globale est automatiquement calculée et divisé par le nombre total de paramètres (entrée ou sortie) afin de le transformer en un pourcentage. Si le résultat obtenu est égal ou supérieur à 30 pour cent, l'outil est considéré comme ayant une influence sur les éléments en lien avec la cellule. Les figures 4 et 5 montrent les exemples d'analyse de l'outil Cloée.

Input	Sustainable development				Remanufacturing system					
	Eco	Env	Soc	Tech	design for reman (product)	reverse supply chain	information flow in reman system	employee knowledge n skill	reman operation	commercialization reman product
A. CLOEE										
1 Number of component				1		0.5				1
2 Environmental impact of component's material	1		0.5							
3 Environmental impact of component's manufacturing	1									
4 Environmental impact of component's distribution	1									
5 Environmental impact of component's reuse										
6 Environmental impact of component's remanufacturing	1				1	1	1	1	1	1
7 Environmental impact of component's recycling										
8 Environmental impact of component's incineration										
9 Environmental impact of component's landfill										
Total	0	4	0	3.5	4	2.5	2	1	2	0
percentage	0%	44.44%	0%	38.89%	44.44444444%	27.77777778%	22.22222222%	11.11111111%	22.22222222%	0%

Figure 4: L'analyse de l'outil individuel pour les paramètres d'entrée de CLOEE

Output	Sustainable development				Remanufacturing system					
	Eco	Env	Soc	Tech	design for reman	reverse supply chain	information flow in reman system	employee knowledge skill	reman operation	mercializat reman product
CLOEE										
environmental impact of closed-loop end-of-life scenario		1			1		1		1	
Total	0	1	0	0	1	0	1	0	1	0
percentage	0%	100%	0%	0%	100%	0%	100%	0%	100%	0%

Figure 5: L'analyse de l'outil individuel pour les paramètres de sortie de CLOEE

4.1.2. La grille d'analyse à deux dimensions

La seconde étape est la synthèse. Ici, la grille d'analyse à deux dimensions a été introduite pour insister sur fait qu'il faut considérer simultanément ces deux perspectives. Nous avons recueilli les résultats obtenus à partir de l'analyse de l'outil individuel et représenté les résultats de manière à ce que les utilisateurs puissent mieux comprendre les enjeux d'un tel outils et en tirer des conclusions.

La grille d'analyse à deux dimensions a été développé en se basant sur le concept d'une matrice qui est composé de six colonnes des six éléments du système de remanufacturing et quatre lignes qui représentent les quatre piliers du développement durable (marqué Ec, En, So and Te). Chaque outil (ou méthode) a ses propres matrices d'entrée et de sortie. En référence au tableau de l'analyse de l'outil individuel, un critère qui atteint le seuil de 30% a été donné pour un score dans la colonne et la ligne couplée de la grille d'analyse de deux dimensions. Il est important de vérifier que les critères existent dans les deux perspectives. Le tableau 2 montre l'exemple de la grille d'analyse à deux dimensions pour l'outil CLOEE (paramètres d'entrée et de sortie)

	CLOEE Input						CLOEE Output					
	a. Design for remanufacturing	b. Reverse supply chain remanufacturing system	c. Information flow in skills	d. Employees' knowledge & skills	e. Remanufacturing operation remanufacturing product	f. Commercialization of remanufacturing	a. Design for remanufacturing	b. Reverse supply chain remanufacturing system	c. Information flow in skills	d. Employees' knowledge & skills	e. Remanufacturing operation remanufacturing product	f. Commercialization of remanufacturing
1. Economic												
2. Environment	1						1	1		1		
3. Social												
4. Technical	1											

Tableau 2: La grille d'analyse à deux dimensions pour l'outil CLOEE (paramètres d'entrée et de sortie)

La même démarche est faite pour les autres outils et méthodes analysés. Le tableau 3 représente les paramètres de sortie superposés de tous les outils / méthodes analysés et qui permettent un certain nombre d'interprétation. Il peut être utilisé, par exemple, comme une source d'informations pour envisager la création d'un nouvel outil / d'une méthode à l'avenir en se concentrant sur la zone la moins explorée. Il est clair que le tableau ci-dessus ne représente pas l'état réel des outils / méthodes DfRem car seuls 12 outils / méthodes ont été analysés. Toutefois, elle représente la fonction des méthodes proposées et permet de capitaliser l'expertise existante. Au plus on aura d'analyse faite sur des outils / méthodes existantes, au plus on aura d'informations sur l'état des outils / méthodes DfRem.

	1	2	3	4	5	6	Total
Ec	2	2	6	1	5	0	16
En	3	1	5	0	5	0	14
So	0	2	2	1	1	0	6
Te	4	2	9	1	9	0	25
Total	9	7	22	3	20	0	

Tableau 3: Les paramètres de sortie superposés de tous les outils / méthodes analysés

4.2. Une méthode pour choisir les Outils / Méthodes DfRem

La deuxième partie de cette proposition vise à aider les concepteurs à choisir les outils / méthodes DfRem appropriés selon leurs besoins. En utilisant le cadre de travail et le tableau de remanufacturabilité de la proposition 1, et les méthodes de classification précédentes, cette méthode fournit aux utilisateurs des informations précises sur les outils / méthodes dans un temps court. En termes de principe, cette méthode proposera aux utilisateurs l'outil(s) / la méthode(s) existant approprié et analysé selon l'objectif que les utilisateurs veulent atteindre. Elle deviendrait ainsi un moyen pour introduire les outils / méthode académiques de DfRem aux utilisateurs industriels d'une manière guidée et systématique.

4.2.1. Les paramètres de sortie des outils/méthodes de DfRem dans le tableau de remanufacturabilité

Le tableau de remanufacturabilité, qui fournit les différents objectifs des aspects de la remanufacturabilité est utilisé pour classer les sorties des outils/méthodes existants. Les sorties classifiées dans la table de remanufacturabilité fonctionnera comme une base de données pour le démonstrateur de la méthode. Une méthode systématique avec les étapes et des règles spécifiques a été appliquée afin de classer ces sorties comme on le voit dans la figure 6.

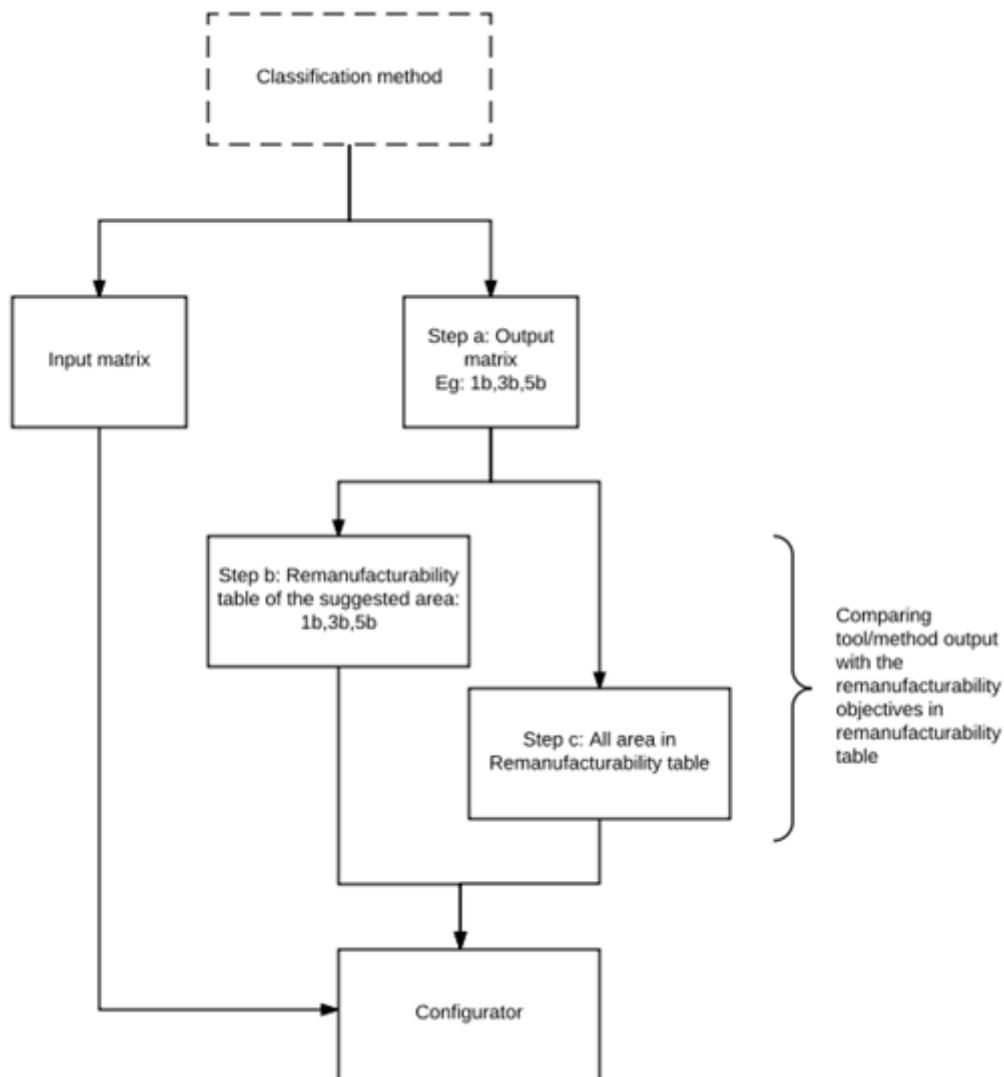


Figure 6: Diagramme qui montre le flux pour classer l'entrée et la sortie d'un outil dans le tableau de remanufacturabilité afin de pouvoir l'utiliser comme une base de données pour la configuration de la Méthode de choix d'outil/méthode

4.2.2. Un démonstrateur pour Choisir l'outil/la méthode

Au cours de cette étude, un configurateur a été développé pour permettre la manipulation de nos concepts par les utilisateurs. Voici les deux fonctions pour ce configurateur:

- a) Une interface pour l'utilisateur afin de choisir l'outil/méthode: Cette partie nécessite de connaître le besoin (s) des utilisateurs et les informations sur le remanufacturing comme les entrées que manipule l'utilisateur. Les utilisateurs pourront obtenir un/des suggestion(s) de l'outil(s) /méthode(s) approprié avec son / leur liste des entrées et sorties. Les étapes de la méthode pour choisir l'outil/la méthode est représenté dans la figure 7.

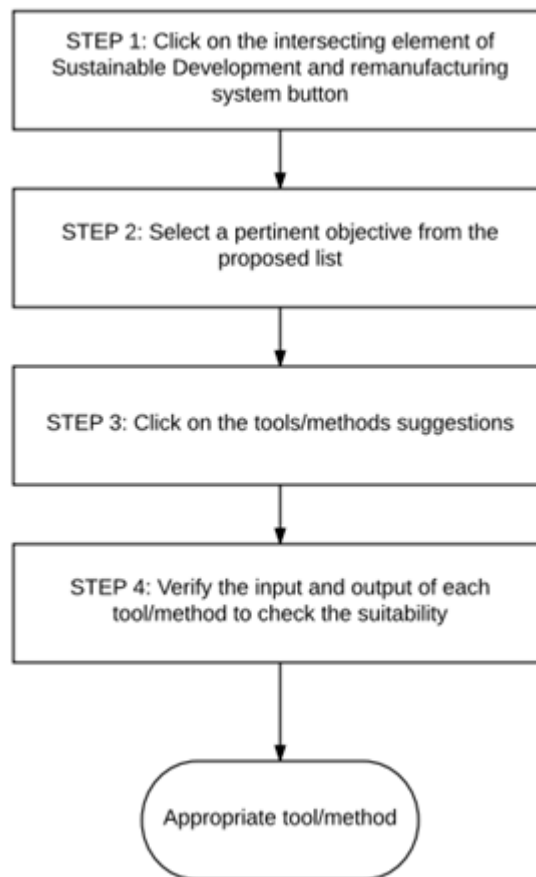


Figure 7: Les étapes à suivre sur le démonstrateur pour choisir l’outil/la méthode

- b) Une interface pour la méthode de classification où l'utilisateur peut saisir des données sur le nouvel outil /la méthode et les enregistrer dans la base de données. Cette partie oblige les utilisateurs à saisir les entrées et les sorties du nouvel outil / méthode analysé dans le tableau d'analyse de l'outil individuel pour la Méthode de classification présentée en 4.1.

Le modèle IPO qui représente la vue d'ensemble des méthodes et configurateurs proposés, leurs interdépendances et leurs contacts avec les utilisateurs est représenté dans la figure 8.

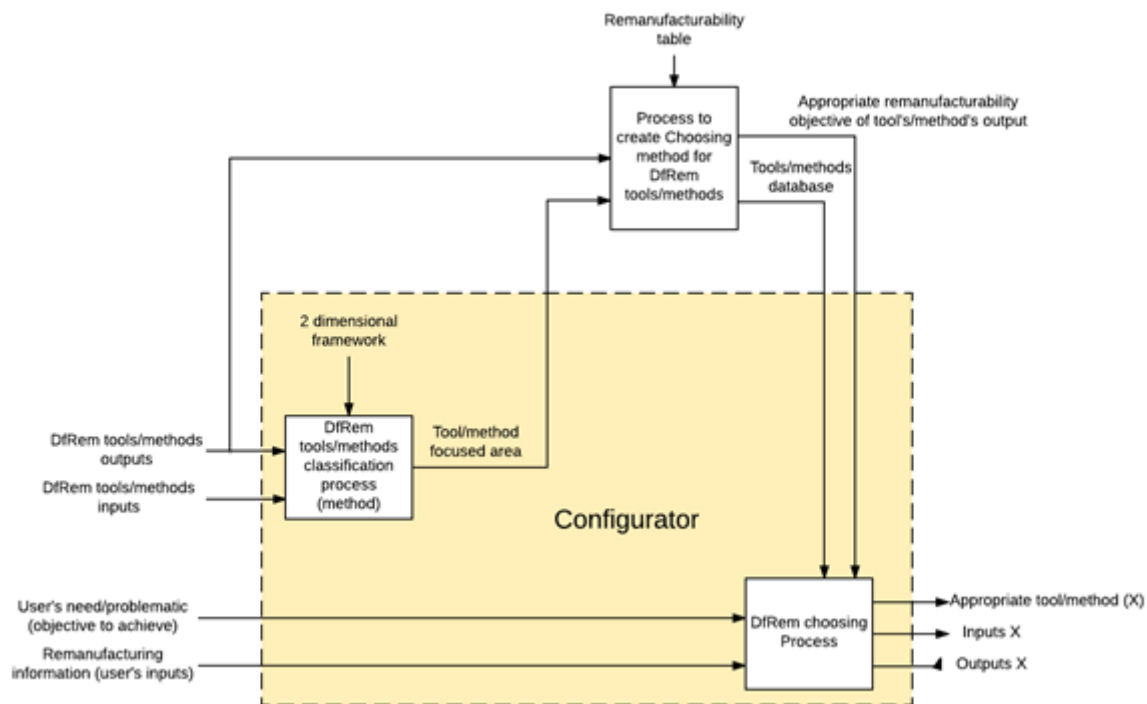


Figure 8: Le modèle IPO pour les méthodes et le démonstrateur proposés

4.3. Validation

Deux études de cas sont créées pour illustrer l'application des méthodes et l'usage du démonstrateur. L'objectif principal de ces études de cas est de montrer comment cette méthode fonctionne du début à la fin dans des conditions données spécifiques. Un scénario de modélisation est créé, qui se compose d'informations sur l'entreprise, sur la description du problème et sur les objectifs de l'entreprise. La première étude de cas est destinée à la recherche des outils / méthodes académique qui aideront l'entreprise à atteindre: "une collecte efficace du produit usagé selon les points de vues économiques, environnementaux, sociaux et techniques". Le deuxième cas d'étude met en évidence les fonctions d'entrées de la méthode/de l'outil en choisissant un outil approprié. Cette étude de cas met l'accent sur l'objectif "niveau de performance de grande capacité" selon les points de vues économique + processus de Remanufacturing.

5. Conclusion et perspectives

Ce travail permet de contribuer à l'intégration des aspects du développement durable dans les systèmes de remanufacturing.

Dans cette thèse, on a :

1. Caractérisé les produits remanufacturés et les processus, selon le point de vue du développement durable
2. Classifié et aidé au choix des outils ou des méthodes de remanufacturing pour améliorer le remanufacturing durable

Pour atteindre ces objectifs, un cadre à deux Dimensions (a Two Dimensional Framework for Remanufacturing - 2DFR), a été proposé. Il combine les perspectives liées au développement durable et celles liées au système de remanufacturing. Une liste des contraintes liées au remanufacturing est ainsi proposée dans la première partie de la thèse selon ces deux perspectives. Elle a été validée comme un guide de conception pour le remanufacturing lors d'un atelier dans le cadre du projet européen ERN (H2020). Le 2DFR est ensuite utilisé dans la deuxième partie de la thèse pour développer la classification des outils et des méthodes de remanufacturing. Enfin, une méthode pour guider l'utilisateur dans le choix des outils et méthodes de remanufacturing est proposée. Elle est créée à partir de la liste des caractéristiques du remanufacturing apparues dans la première proposition et de la méthode de classification mentionnée précédemment. Un démonstrateur qui fonctionne comme une interface pour les deux méthodes de classification et de choix des outils est développée. Des études de cas permettent d'illustrer son utilisation.

Les caractéristiques pour des produits et processus de remanufacturing durables définies dans la première proposition offrent ainsi aux utilisateurs un guide complet lors de la conception et de la prise de décisions. La deuxième proposition, quant à elle, encourage l'utilisation par l'industrie des outils et méthodes académiques existants liés au remanufacturing.

Certaines améliorations ont été suggérées pour les deux propositions en termes de:

- validation: les deux propositions doivent être validées au cours d'un cas réel dans l'industrie
- exhaustivité: il est suggéré d'enrichir les bases de données avec plus de caractéristiques et d'outils / méthodes de remanufacturing
- automatisation: une analyse automatique est suggérée pour la seconde proposition afin de réduire au minimum l'influence de l'utilisateur sur la classification des outils.