INFERENCE CONFORMITY BASED ANALYSIS FOR EOL PRODUCT RECOVERY OPTIONS DECISION MAKING

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Declaration

I declare that this thesis hereby submitted to National University of Singapore for the partial fulfillment of the degree of Doctor of Philosophy has not previously been submitted by me for a degree at this or any other university, that it is my own work and all the sources have been quoted and acknowledged by means of complete references.

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Ng Yen Ting

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Summary

Owing to the growing population, environmental problem, social pressure and legislative initiative and economic gain, sustainable development is an imperative act to accomplish the fundamental needs of the nations and protect the environment. Legislation such as Waste Electrical and Electronic Equipment Directive (WEEE) in Europe and Resource Conservation and Recovery Act (RCRA) in the United States are leading the society towards sustainable development. One of the strategies to achieve the ultimate goal is through EoL product recovery. This goal can be best achieved by encouraging multiple-reuse of good condition parts or products as well as material. However, the decision on judging a good EoL part or product is subjective. Therefore, a comprehensive framework to assess the condition and recoverability of part or product, and models to quantify the condition is necessary prior to making decision for certain recovery option.

The objective of this thesis is to develop a comprehensive assessment framework and models integrating technical, time, economic and environmental aspects to evaluate recoverability of EoL product and provide optimal solution. The assessment framework considered product life cycle associated with the information that can use as reference in product recovery stage. A technique that uses manufacturing information as reference data in this thesis called Inference Conformity Based Analysis (ICoBA). This technique is applied in characterization of EoL product condition, which it quantifies the EoL product condition in terms of time, cost and environmental impact. Subsequently, the final decision is made based on the three aspects using Multi-attribute Utility Theory

(MAUT) decision analysis. This decision analysis method standardizes the quantified values in 0 to 1 scale so that aggregation of total score can be performed.

In order to demonstrate the application of the assessment framework and models in real business environment, real cases collected from industrial partner on consumer product was studied. Compressor block and crankshaft are studied to demonstrate the considerations in decision making for part recovery. The case study has confirmed the readiness of the framework and models as a tool to evaluate products at the end of their life. Besides, the analyzed outcome enables decision makers to disclose the risk associated with the decision. It eliminates the subjectivity of weightage allocation, thus improving the quality of the decision. The results are in good agreement with the basic theory that recycle is recommended in the first scenario with overall 0.01 utility value gain as compare to making new. On the other hand, remanufacture is recommended in the second scenario with the highest utility of 0.794 for crankshaft. Remanufacture has 0.628 utility gain as compared to making new and 0.71 utility gain as compared to recycle option.

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List of Abbreviations

AHP	-	Analytic Hierarchy Process
BAU	-	Business-as-usual
BOM	-	Bill of Materials
CAA	-	Clean Air Act
CAD	-	Computer-aided Design
CBA	-	Cost Benefit Analysis
CBR	-	Case Based Reasoning
CO_2	-	Carbon Dioxide
CSR	-	Corporate Social Responsibility
CWA	-	Clean Water Act
EELS	-	Electron Energy Loss Spectroscopy
ELECTRE	-	Elimination Et Choix Traduisant la Realité (Elimination and Choise Expressing Reality)
ELV	-	End of Life Vehicle Directive
EoL	-	End-of-life
EU	-	European Union
EWRQ	-	Environmentally Weighted Recycling Quotes
GHG	-	Greenhouse gas
GRA	-	Grey Relation Analysis
ISO	-	International Organization for Standardization
LCA	-	Life Cycle Assessment

LCC	-	Life Cycle Costing
LCE	-	Life Cycle Engineering
LCM	-	Life Cycle Management
LPEUR	-	Law for Promotion of Effective Utilization of Resources
MADM	-	Multi-attribute Decision Making
MAUT	-	Multi-attribute Utility Theory
MAVT	-	Multi-attribute Value Theory
MCDM	-	Multi-criteria Decision Making
MODM	-	Multi-objective Decision Making
MOGA	-	Multi-objective Genetic Algorithm
NGO	-	Non-governmental Organization
NUS	-	National University of Singapore
OECD	-	Organization for Economic Co-operation and Development
OEM	-	Original Equipment Manufacturer
PLC	-	Product life cycle
RCRA	-	Resource Conservation and Recovery Act
REACH	-	Registration, Evaluation, Authorization and Restriction of Chemical
ReSCICLED	-	Recovery System Modeling and Indicator Calculation Leading to End-of-life Conscious Design
RoHS	-	Restriction of Hazardous Substances Directive
PROMETHEE	-	Preference Ranking Organization Method for Enrichment Evaluations

SIMTech	-	Singapore Institute of Manufacturing Technology
SMART	-	Simple Multi-attribute Rating Technique
TOPSIS	-	Technique for Order of Preference by Similarity to Ideal Solution
UN	-	United Nation
UNEP	-	United Nations Environment Programme
WBCSD	-	World Business Council for Sustainable Development
WEEE	-	Waste Electrical and Electronic Equipment Directive

CHAPTER 1

Introduction

This chapter provides a brief description on sustainable development that leads to the research area of EoL product recovery. It also covers the motivation of EoL product recovery, and challenges behind it. Following the background knowledge, research objective is formed and research questions are identified. The overall methodology of this study is presented to provide guidance for reader. Finally, thesis outline is explained at the end of this chapter.

1.1 An Overview of Sustainable Development

Sustainable development is the progress that meets the needs of the present without compromising the ability of future generations to meet their own needs, according to United Nation document [1]. Besides, poverty, environmental impact and population growth are closely related to sustainable development, however, it remains challenges in the development process [1]. An escalation in number of population heightens the pressure on resources, where the society may compromise its ability in many ways to meet the fundamental needs of people by overexploiting resources. Thereby, several environmentally friendly concepts have been initiated in the area of manufacturing. The familiar concepts started with clean production [2], lean production [3, 4], green manufacturing [5, 6], sustainable manufacturing [7-10] and environmentally conscious manufacturing [11-14], which are conceptualized around the reduction in resource consumption (includes energy, material and labor) for producing a product. Processes used to achieve this should minimize negative environmental impacts, be safe for communities and are economically sound – thereby fulfilling the three arms of sustainability - social, economic and ecological. Some of the reasons for sustainable development are explained as follow.

- Growing population

  Population growth is closely linked to the sustainability of development, which the world reached 7.2 billion inhabitants living on the planet in 2013 [15]. As population increases, nations develop followed by urbanization and infrastructure development, energy and transport expansion. Alongside with the population trend, it gives an indication to the world production and consumption pattern to support the society needs. According to the publication by GRID-Arendal (a center collaborating with UNEP), global consumption of key raw materials is surging high in recent decades, such as construction materials, industrial minerals, metals, non-renewable organics and agricultural and forestry products. Subsequently, the raw materials that are turning into consumer products generate waste in years later [16].

- Environmental problem

  Following on the population growth, more products are generated to cater for the needs. However, it has been notified that the generation of products introduces negative impact to the environment during the manufacturing and usage period, as well as waste management at the end of use [17]. The environmental burden depends on the nature of raw material being processed, the technology and the amount of discarded waste from the chain of the processes and also user behavior. Oftentimes, manufacturing wastes are ended up in hazardous category. This is somehow contributing to the communicable diseases, climate change issue, ozone layer depletion and also natural disaster incidents.

- Social pressure

In addition, society is aware of healthier living environment as environmental problems threaten to human health and climate. Both household consumer and industry client demand and put pressure to the manufacturers for producing product with better environmental performance. As such, Corporate Social Responsibility (CSR) has become one of the environmental performance measure criteria that taking responsibility for the impact on society. This concept requires industry to make change towards environmental and society benign as a whole. In order to handle the change, industry shall act proactively by incorporating environmental features into their existing business operation. Moreover, evidence suggests that implementation of CSR is increasingly important to bring the competitiveness of enterprises [18, 19].

- Legislative initiative

With growing population, environmental problem and social pressure, enforcement of environmentally sound legislations play the critical role in moving sustainable development to a better position. For example, Electrical and electronic manufacturer in EU must conform to the EU legislations of Waste Electrical and Electronic Equipment Directive (WEEE) [20] and Restriction of Hazardous Substances Directive (RoHS) [21]. End of Life Vehicle Directive (ELV) aims at making dismantling and recycling more environmentally friendly [22] and Registration, Evaluation, Authorization and Restriction of Chemical (REACH) protects human health and the environment [23]. Environmental laws in the United States such as Clean Air Act (CAA) [24], Clean Water Act (CWA) [25], Resource Conservation and Recovery Act (RCRA) [26] and so on. Besides, national and international nongovernmental organization also plays a significant effort in this area, establishing standards and initiative. The popular standards are ISO 14000 for environmental management [27], ISO 50001 for energy management [28] and ISO 20121 for sustainable events [29].

All of these policies oblige manufacturer to take responsibility for the whole life cycle of their products. As a result, it is compulsory for manufacturer to manage the product after its end-of-life. Although the regulations are gradually implemented in some region, manufacturers have to get prepared in managing EoL product for effective recovery strategy.

- Economic gain

Another reason behind sustainable development is to obtain economic benefit from resource optimization activity. This can be achieved if product take back regulation is fully enforced and manufacturer finds way to reuse the resources via product recovery. Manufacturer might receive incentives and tax reduction in producing environmentally friendly product. However, the hidden opportunity comes from economical viable product recovery which the recycled material feed as input and used part or product is renewed for another lifetime.

In summary, the growing population is responsible for the depletion of resources, other factors such as inefficient resource consumption, waste generation, pollution from industry and wasteful consumption behavior are equally bad to the environment. As a result, sustainable development is an imperative act to fulfill the fundamental needs of the nations, at the same time protects the environment.

1.1.1 Strategies in Sustainable Development

Looking at the rate of destructive activities to the environment, the world must take quick action onto sustainable development. According to the objectives set by United Nation (UN) and European Commission, the overall aim of sustainable development strategy is largely predominant in the area of environmental, such as [30]:

- Climate change and clean energy;
- Sustainable consumption and production;
- Conservation and enhancing resource base;
- Reorienting technology and managing risk;
- Merging environment and economics in decision making

In order to improve the synergies, regulations and policies play a prime important role in stitching the sustainable strategies. The regulations and policies provide a platform for improving the coordination with governments, businesses, NGOs and citizens to take part in the sustainable development. On the other hand, education, research and public finance are the vital instruments in facilitating the strategies translate into a more sustainable production and consumption patterns. As such, there is plenty of room for advancement in the area of sustainability.

1.2 Research Motivation

In view of the strategies for sustainable development, sustainable approach in product development is one of the enablers [31, 32]. In part, this attention is also motivated by legislation enacted by a growing number of countries that imposes greater responsibilities on manufacturers for managing their EoL product. With the assumption of take back regulation is enacted, there will be growing concern on product manufacturers to manage the products they manufacture once the products reached EoL stage.

The motivation for EoL product recovery comes from the strategies mentioned above. Product recovery conserves and enhances resource base by salvaging the embedded resources from end-of-life product. There are two possible scenarios for EoL product recovery. The first scenario depicted how's a product manufactured and it is returned to the OEM at the end of life (in **Figure 1-1**). For a bulky product, the products directly take back from consumer by collecting agents, who are the OEM or retailer. On the other hand, the OEM or retailer acts as the product return point for the small consumer product. And finally all the collected products return to OEM. During the recovery stage, the EoL product is possible for several recovery options. Recovery manager at OEM has to judge whether gives the product a new lease of life, recycle the material for manufacturing input or transforms the EoL product to other product system.

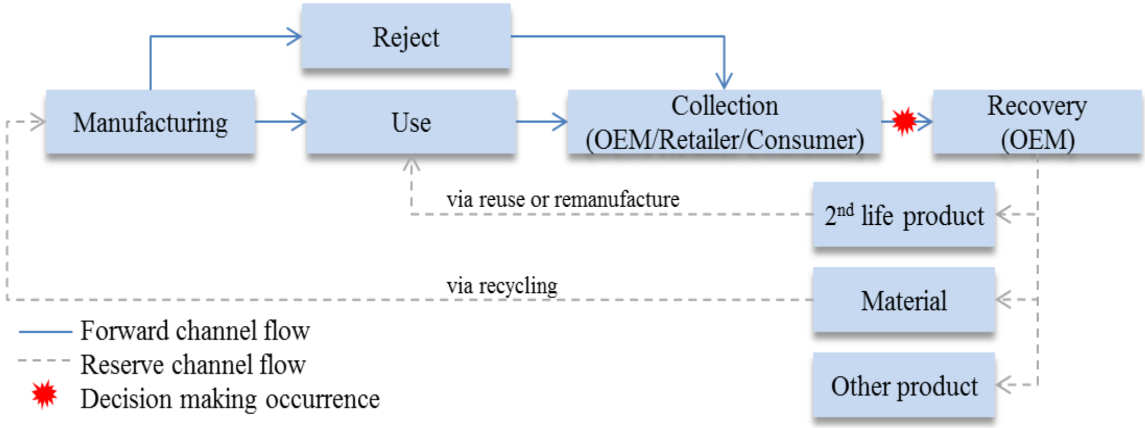


Figure 1-1 Product forward and reverse channel managed by OEM

However, current practice happens where the collection of EoL product is done by third party in particular area or region is shown as second scenario (in Figure 1-2). The third party waste collector (third party A) could be also the waste recycler (third party A). In other case, the EoL products collected by third party A are sent to third party B for recovery. In both cases, all the collected products are managed by third party at product recovery stage. Similarly, there are several product recovery options at the recovery stage. The third party recovery manager ought to give a serious thought on managing the EoL product in efficient and profitable way. There are possible options for selling back the new lease of life product to the OEM, convert the EoL product into material and sell it back to the manufacturer or sell the recovered product and material to other manufacturer.

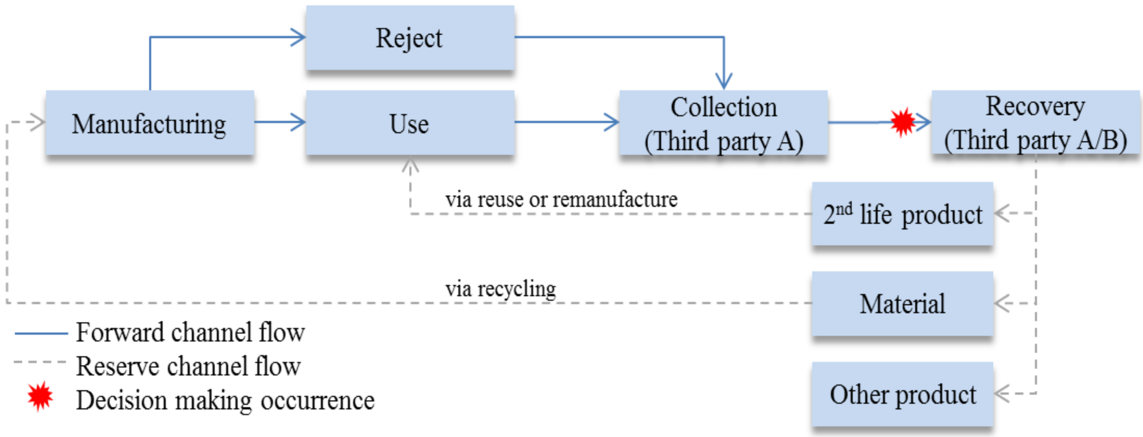


Figure 1-2 Product forward and reverse channel managed by third party

In both scenarios, EoL product recovery process can lead to sustainable consumption and production. However, there is major challenge on the judgment for appropriate recovery option after the EoL products are collected for both scenarios (as shown with the explosion marking in **Figure 1-1** and Figure 1-2). Thereby, the research for methods to assess EoL product condition and models is required to make informed decisions for EoL product recovery.

In other to reduce environmental burden yet stay competitive in the business, OEM or third party recycler might need to look time, economics and environment aspects. With the proper life cycle assessment (LCA) approach, product recovery analysis able to identify the life cycle cost and environmental impact. Besides, an efficient operating manner for EoL product recovery could bring advantages to manufacturers include: meeting customer demands, protecting aftermarkets, reducing manufacturing costs, promoting environmentally responsibility and preempting regulation.

- *Meeting Customer Demands*

Customer expectations are driving some manufacturers increasingly involved in EoL product recovery. For instance, in IT hardware industry, customers are increasingly expecting OEMs who supply the equipment take back the outdated equipment when they install the new ones. If the outdated equipment is properly managed, OEMs could recover the standard parts and sell it as spare part at lower price. It reduces waste to the environment, meantime it aids in extending others equipment life to meet customer demand.

- *Protecting Aftermarkets*

Aftermarkets refer to follow-on products that are used in maintaining or enhancing previous purchase, and they are always profitable for OEMs [33]. OEMs may recover their products to deter independent remanufacturing firms from selling cheaper option of products, therefore prevent potential losses on market share and brand image. Otherwise, OEM can certify the part recovered by the assigned third party recycler and then distributors sell it in the second hand market.

- *Reducing Manufacturing Costs*

Many companies have discovered that valuable materials and embodied energy that can be recovered largely in reuse, followed by remanufacturing, and recycling. Moreover, costly components, materials and embodied energy from durable product often can be further refurbished to substitute for virgin parts. Thereby, mixture of good condition part from EoL product and new part use in manufacturing for new product could reduce the cost tremendously. Although the cost of labor and factory rental (for developed country) as a proportion of the total cost of production is unlikely to be avoided, reusing of recovered part of material will diminish the cost.

- *Promoting Environmentally Responsibility*

  Many well-known companies have enacted waste recovery related programs to enhance the environmental image of their brand, for instance Hewlett-Packard [34] and Xerox [35]. The recovering used equipment in Xerox improved customer experience and also enabled company to address minimization of waste throughout the design, make, use and EoL stages [35]. Furthermore, increasing use of recycled material, remanufactured or reused part in new product design encourages environmentally sustainable business practices.

- *Preempting Regulation*

  With the improved product design, environmental friendly element becomes an inherent loop for new product life cycle that able to produce greener products. This anticipate manufacturer reduce the pressure from new or expanded legislation.

1.3 Issues and Challenges

Despite of the benefits gain from EoL product recovery, a number of prominent issues are worth noting in current product recovery industry. It is noted that product recovery industry is largely unorganized as compared to traditional manufacturing sector.

- *Information Shortage on Returned Product*

  In current product recovery industry, most of the independent remanufacturing or recycling firms operate with no formal agreement with suppliers or customers. Information associated with products often cannot be retrieved; therefore intensive inspection and testing are required in order to obtain product information. Even if the design information could be obtained from manufacturer, the residual life and remaining value of the product are unknown. Hence, shortage of readily available information is the biggest barrier to making informed decision and thus efficient recovery operation.

- *Supply Driven*

  The traditional manufacturing industry is demand-driven, where suppliers are obligated to meet manufacturers demand. On the other hand, current product recovery industry is supply driven, where the industry operates based on products bring in by reverse supply chain, and tries to generate demand for the recovered products. The product recovery industry has no control over the rate of returned products. In most cases, independent firms have to predict the rate of product returns based on primary market demand.

- *Hefty Investment and Technology Availability*

  Product recovery comes with data collection, analysis and decision making. These processes require advance technologies which might results in high capital expenditure and maintenance cost. For example, some of the emerging technologies such as 3D printing and machine to machine (M2M) are becoming popular tools that incorporated resources optimization process. However, it requires new learning curve and heavy investment. There might also be technology required which isn’t available in the market yet and many organizations can’t afford to build their own technology to solve the puzzle. On the other hand, product recovery industry largely remains operating in manual process, as most of the time reverse engineering is required to understand the product function. This resulted in slow, costly, erratic, and inefficient product recovery process. Moreover, one of the problems along with product recovery processes is the random failure mode that required different skills and tools with high level of flexibility to solve, as well as the absence of complete information associated with the products.

- *Low Profit Margins*

The problems mentioned above engender product recovery industry operates on high costs, and thus low profit margin or even negative margin. This is because of unknown time, quality, quantity and source of returns, together with the shortage of information that required assessing the identity of products.

- *Lack of Expertise*

Expertise in product recovery is new and not readily available in the open market. There is shortage of expert in this domain even at advance countries. The knowledge is not well organized in a mature state like primitive manufacturing sector. Each industry needs customization solution adds the complexity to standardizing and sharing the knowledge of product recovery effectively. However, many of this knowledge can be trade secret within an organization and this will even slow down the process for wide adoption.

- *Lack of Understanding*

Though product recovery (ie. recycling) is not new, only advance countries are interested to practice today. One of the reasons for negligent in product recovery is due to the lack of education in emerging countries about the benefit of resources optimization. Environmental effect is a future event and many leaders might underestimate the impact. However there are plenty of scientific papers and methods being published now which required to share with more industry players.

- *Consumer Expectation*

From a customer perspective, remanufactured product and low-end product are different. Even if function wise both products are of same quality, customer is not fully positive about remanufactured product. Customer's willingness to pay toward remanufacturing is necessary to be understood [36]. Many customers do not want the tag of remanufactured product especially for high–end products such as parts used in an aircraft [37].

- *Government Incentive*

In many developing countries, where most of the manufacturing is carried out, resources can be cheaper than the process to go through the resources optimization. At the same time, emerging countries might be blinded by the objective to get more done in shorter time to increase productivity as material and energy in these countries are usually cheaper. The local government can further disrupt the industry by providing incentive such as subsidized energy and tax free raw material. This discourages product recovery economically.

- *Regulation*

In many countries, the regulatory have not planned or emphasize the importance of product recovery for resource optimization. Industry becomes short of guideline and enforcement to adopt the idea of resources optimization. The European regulatory design and limit the waste for various industries such as CO_2 released from road transport, this has enforced the industry to innovate for resources optimization to continue operating [38].

The benefits gain from salvaging EoL products becomes increasingly attractive; yet managing returned products optimally remains uncharted. The silver lining behind the cloud of problems are journals which develop methods to quantify the condition of returned products – in the form of benefits in time, cost and environmental impact. Taking the resources involve in making the new product as base case, decision maker able to make fair comparison between new production and other recovery options like remanufacturing and recycling. As the result, a comprehensive recovery system alongside readily available product information is needed to enable informed decision making.

1.4 Objective and Research Questions

Understanding the research topic motivations and challenges has led to deriving of research objective. The objective of this study is to develop a research framework, focussing on quantifying the EoL product condition and making rational decision on selecting EoL recovery options, namely reuse, remanufacturing and recycle. The purpose is to utilize recovered materials from EoL product to reduce material and energy inputs.

This study contributes to understanding of knowledge about resources optimization and its application for the manufacturing industry. Reuse, remanufacturing and recycle are expected to contribute to sustainability by saving material and energy resources as well as decreasing waste while collecting used components and giving them new life. With this objective in mind, it is able to realise the short term goal of building competitiveness for manufacturing industry by identification of the best practices and the new eco-innovations. And also define the best strategies for the creation of new business activities in the field of resources optimization. On top of that, the research objective allows manufacturer fulfil the long term goal by inheriting the closed-loop product life cycle concept in product design. This requires radical change where long life products are seen as the normal way of manufacturing to prolong usage life so that high value resources can be optimized.

As a result the resources optimization concept for manufacturing industry and the development path towards utilizing scientific methods will be developed. This concept includes framework to assess recoverability, description about the needed information and services, value networks, material and information flows and decision model for business sense.

In order to achieve resource optimization, the first task of the study is determining the optimal product recovery option. Secondly, the research also aims to create new openings and understanding by integration of the experience of industrial system. The research objective is then led to the following three main questions.

1.4.1 Research Question 1

The first research question is: *How to characterize EoL product condition?* This question is regarding to knowing the condition of EoL part/product. It challenges about the process of determining the condition of the EoL product so that the values can be useful for product recovery decision analysis. The quantified values are used in analyzing product recovery gain and loss in various perspectives.

1.4.2 Research Question 2

The second research question is: *How to make an accurate and consistent decision for selecting EoL product recovery option?* The question concerns with the accuracy and consistency of result in choosing the appropriate recovery option. It challenges about the model developed whether it is detail enough to count for accurate result and the deviation. Also, the question asks about the approach or method to ensure a reliable outcome under random returned part/product conditions.

1.4.3 Research Question 3

The third research question is: *How can the developed method and model be applied on different category of products for EoL product recovery decision making?* This question relates to the feasibility of the approach or method for decision making in EoL product recovery. The question asks about the generalization of the approach or method to a diverse range of industries or products.

1.5 Research Methodology

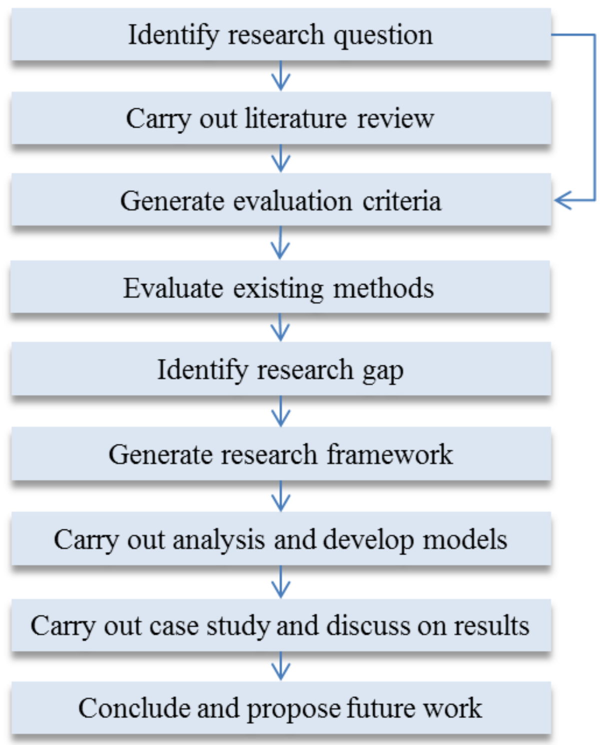


Figure 1-3 Research methodology

A systematic way of carrying out this research is shown in Figure 1-3, where it starts from identifying research question based on the background knowledge. The research question is then leading to probing on specific issue that require extensive literature search. Therefore, a comprehensive literature search has been done. The literature search covers book chapters, scientific journals, conference proceedings, dissertations, official reports, databases, websites and working papers from credible institutions. With ample details on particular topics, a set of criteria is generated to address the research question, meanwhile evaluate on the existing methods that are closely related to the topic. The research gap on the existing methods is further crystalized and thus form a solid foundation for the study.

Data used in this study are collected directly from the manufacturer, including product specification, bill of materials, reliability test data, cost data, energy consumption data, and other operation and management related information. In the case of confidential or unavailable data, supplement data are collected from credible sources such as scientific journals.

Mathematics computation and plotting of utility curves are carried out using Microsoft Excel. The environmental impact analysis is performed using SimaPro™ software version 7.0. And decision trees are generated with the help of add-ins software for Microsoft Excel named Treeplan®.

1.6 Thesis Outline

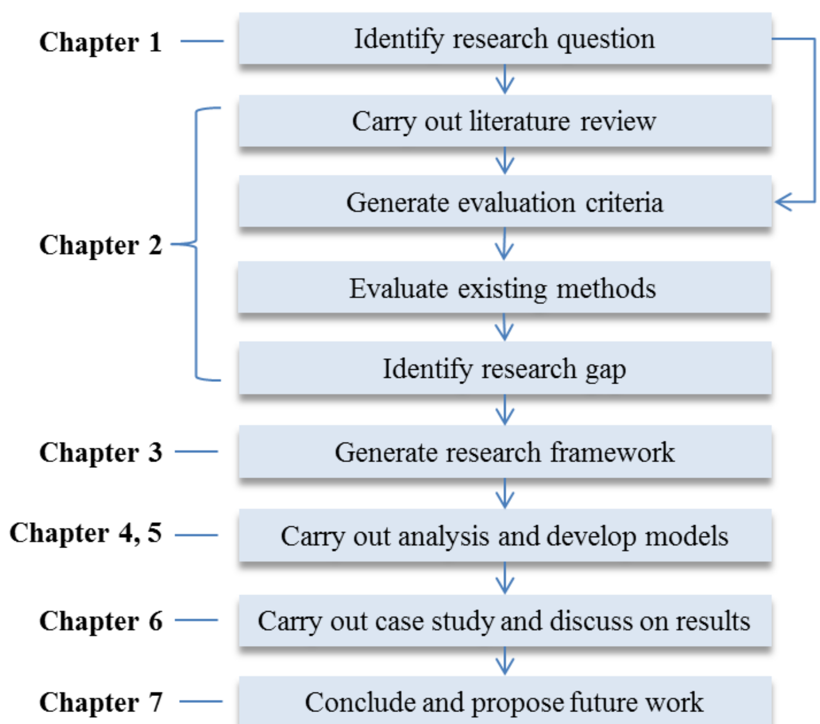


Figure 1-4 Outline of thesis

Figure 1-4 shows the outline for this thesis. A comprehensive literature review on theoretical groundwork of the research is presented in Chapter 2. The overview of EoL product recovery was described thoroughly as well as the important aspects that affect the decision making in selecting best recovery option. Decision analysis methods are critically reviewed, categorized, evaluated and discussed. Accordingly, a set of criteria to evaluate multi-criteria decision making method is identified. The existing methods are evaluated based on the set of criteria and finally research gap is identified with regard to the shortcoming of the existing methods. This chapter is referred as the basis of the model development.

Chapter 3 presents the research framework, which it consists of process flow, information flow and material flow. The process flow illustrates company goal setting steps, product life cycle steps, analysis steps, decision making steps and lastly verifying step. The framework in this chapter is generalized for all types of product, however, focusing on cast iron product to illustrate the detailed assessment and modeling process.

Chapter 4 explains in detail on determination of EoL product value with refer to new product characteristic using inference conformity based analysis (ICoBA). Besides, EoL product assessment flow is depicted to assess the condition of the product. Time, cost and environmental impact of product recovery are modelled. This is followed by introduction of threshold values (ie. minimum and maximum values) and modelling of the threshold values are carried out. This chapter is devoted to analyze individual part in a product.

Chapter 5 provides the background knowledge on decision analysis that enable user structures a problem, develop model according to the problem and lastly set up action plans based on the analyzed solution. An overview of multi-criteria decision making (MCDM) approaches is introduced in this chapter, followed by the procedure of implementing multi-attribute utility theory (MAUT) in EoL product recovery selection problem. At the end of this chapter, decision tree is presented to exhibit the computation results for ease of visualization.

Chapter 6 evaluates and validates the proposed models using parts in a consumer product in the case studies. Crankshaft and block of refrigerator compressor are selected to illustrate the assessment flow and generate result using the models. Finally, the decision is made based on the best utility value.

Chapter 7 summarizes the main research findings of the thesis covering the critical lessons and results from the research. This chapter also identifies opportunities for future research.

CHAPTER 2

The State of EoL Product Recovery

This chapter presents literature review on decision analysis on EoL product recovery that forms the foundation of the research. The status of research on various means of EoL product recovery options will be presented in the first section, followed by types of indicator that affect decision making in product recovery in second section. As decision analysis is the elemental action that anticipates consequence of end result, a thorough review covers a broad range of decision analysis method from scholarly sources will be presented in third section. The state-of-the-art of multi-criteria decision making (MCDM) for EoL product recovery and criteria for evaluation of decision making in product recovery will be explained in the fourth section. This is followed by evaluation on existing method and comparison on the evaluation results. The research gaps and founding of research needs are described at the end of this chapter.

2.1 Status of Research on EoL Product Recovery

The pursuit of product recovery at end-of-life essentially is one of the stages in product life cycle, which the product goes through product design and development to its ultimate retirement and disposal. EoL occurs at the last phase of product life cycle when the product no longer satisfies user needs. The EoL product that goes through retrieval activity is classified as product recovery. Figure 2-1 shows the hierarchy of product recovery options in the order of preference for environmentally friendly. Reuse, remanufacture and recycle are the common recovery option practice in industry, and thus they are chosen as the EoL recovery options to illustrate decision analysis in this study.

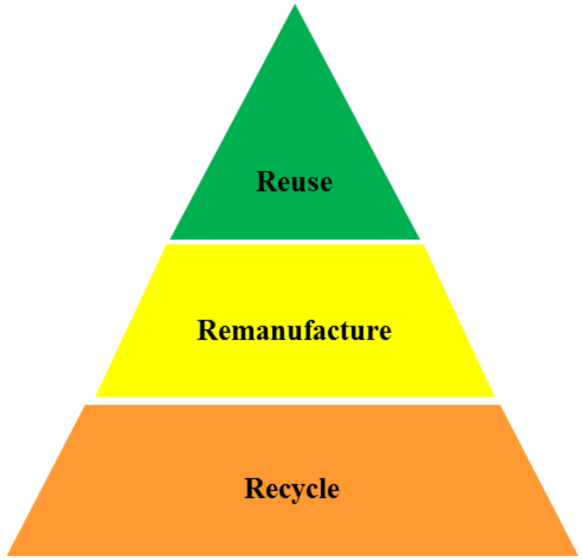


Figure 2-1 Hierarchy of product recovery options

i) Reuse

Reuse is the most environmentally friendly recover option where it requires defect verification and sometimes cleaning of the product. Through this option, lifespan of the used product could be extended in the next cycle of product usage. An extensive of review had been done on the topic of reuse, studies on production line technology [39] and disassembly sequence [40] that support product reuse, and justification on reusability potential [41-44] are found in the literatures. Besides, quality of a reused product is the upmost important verification step in reuse option, evaluation model is studied in the paper reviewed [42]. In the context of this thesis, used part is reused in the similar model of product. Thereby, it is considered as closed-loop recovery.

ii) Remanufacturing

Remanufacturing is the process of product disassembly and restoration of the worn-out part to like new condition [45]. Often, the disassembled part is cleaned, re-machined and reassembled to produce a fully functional product and sometimes superior in performance and longer lifetime than original product. From the literature review, plenty of studies have been emphasized on supply chain models associated with cost or profitability. Used product assessment for remanufacturability is published in literatures [46-48]. In the context of this thesis, the used part will be re-machined to the original dimension and reassembled to the similar model of product. As such, part remanufacturing is closed-loop recovery.

iii) Recycle

Recycling is the primitive end-of-life product recovery practice in industry. It is common to find recycling of waste into material resources, such as aluminum, rubber, pcb and electronics in the literatures [49-53]. However, one shall understand the impact of material recycling before decision is made [54]. For instance, recycling of material is generally more advantageous than combusting in waste-to-energy plant. On the other hand, secondary materials might not fully meet the good standard of quality as raw materials. Considering material recycling from different perspectives could inform a better recycling decision. Studies on the LCA and ecodesign potential for recycling are mentioned in literatures [52, 55]. In general, many works have been studied in the area of WEEE recycling regarding the awareness legislation, market response and consumer behavior [56, 57] . In the context of this thesis, a proportion of recycled used part will be fed to the similar product system and works as closed-loop recovery.

2.2 Important Aspects Affecting Decision Making in EoL Product Recovery

Reuse, remanufacture and recycle are good options for product recovery. However, many other aspects deter the adoption in real business practice [58-60]. Azapagic and Predan proposed a detail and comprehensive set of indicators for identification of sustainable practices for industry [61]. The indicators are particularly useful for measuring the level of sustainability in product recovery perspective. Following section will present the review of research work describes on the dominant factors that influence product recovery in this thesis.

2.2.1 Time

Time is one of the key performance measures in manufacturing, which is usually called manufacturing or production lead time. Similar concept is applicable in product recovery, which the term in this context called recovery time. It measures the average time required to recover a product by the specific recovery option. The recovery time includes disassembly time, processing time, the queue time, setup time, move time, idle time and inspection time. A proper estimation of recovery time in the recovery process is important for the competitiveness that can add to business operations. No literature on time calculation for product recovery is found, however, modeling of manufacturing lead time can be found in the literature [62].

2.2.2 Economic

With regard to economic aspect, profitability is one of the strongest motivations for manufacturers enter into product (or resource) recovery. The economic aspect of product recovery consists of several factors and sub-factors as shown in Figure 2-2. Product recovery value is one of contributions to economic, where manufacturer attempts to retrieve as much value as possible. This is followed by marketing the recovered product for generating revenue to the company. And lastly, robust logistic strategies are the imperative factors in economic advantage as presented by Klausner et al. [63], Subramaniam et al.[64], Joshi [65], Gupta et al. [66] and Rogers et al. [67].

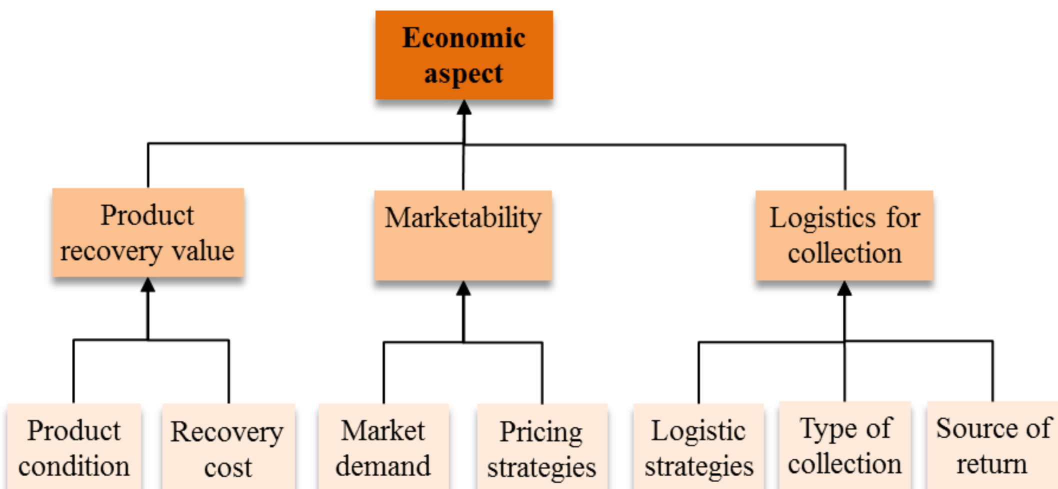


Figure 2-2 Factors and sub-factors of economic aspect

2.2.3 Environmental

Environmentally conscious manufacturing and product recovery has getting more attention with the enforcement of environmental laws and social reputation. Gupta et al., Gungor et al. and IIgin et al. presented extensive survey in this area [12, 13, 68]. As mentioned in the work, alongside with industrial revolution, environmental problems are increasing. This includes depletion of ozone layer, global warming, and reduction of number of landfill sites give hint to the public on environmental awareness. This indicator is particularly important as it greatly influences the potential of product recovery. Product that causes high environmental impact should be reuse. However, collection and cleaning process in recovering the product for reuse also causes negative impact to the environment. In addition, cleaning and remanufacturing of an EoL part possibly impose even more burden to the environment as compare to making new. Consequently, the implementation of recovery strategy is justifiable only if the total environmental load from recovery activity is lower than making new product. A comprehensive analysis using LCA is needed prior to recovery decision is made.

Top ten key environmental indicators presented below are related to pollution issues and natural resources and assets had been identified by OECD [69]. UNEP also share the same view as OECD on the significance of the indicators, which can be found in the report [70]. However, before the key indicators are specified, Opschoor et al. are among the pioneers who look into the environmental indicator [71]. This is followed by Azapagic et al. studied on the indicator framework particularly for industry [61].

1. Climate change 2. Ozone layer 3. Air quality 4. Waste generation 5. Freshwater quality	Pollution issues
6. Freshwater resources 7. Forest resources 8. Fish resources 9. Energy resources 10. Biodiversity	Natural resources and assets

Among the environmental indicators, greenhouse gas (GHG) or carbon footprint emission is identified as the environmental measure. This is because the amount of GHG emissions (mass of CO_2 equivalent) has the direct impact on climate change and global warming. Besides, GHG emission is used as the reduction target in The Kyoto Protocol. Carbon footprint is particularly identified as it is the most standardized in environmental related study and well recognized in the industry. It is also the main category impact found in life cycle assessment result.

As such, carbon footprint is the most appropriate indicator for the work in this thesis due to its relevance, widespread, recognition in environmental policy and general acceptance in industry.

2.2.4 Others

Other aspects like technical, legislative and social responsibility are equally influential in product recovery as indicated in Anityasari’s study [72]. The technical aspect includes product design, machine or process technology change, product reliability and availability of technology for product recovery. Product design in the context of product recovery covers design for reuse [73, 74], design for remanufacture [75-78], design for recovery and design for disassembly [79-84], in order to retain product value [73], reduce product recovery time and cost while increasing product reliability and quality. Moreover, it is undeniable that rapid introduction of advancement equipment and process technologies are to ensure better yield in production and enhance productivity.

The reliability of components is particularly important if the goal is part reuse. Assessment on the quality and reliability for reuse strategy has been presented, where threshold value is determined to set as the standard value for benchmark [85, 86]. This is followed by determination of remaining useful life despite functionality and performance [87-90]. Quantifying the remaining useful life further justify whether the reuse product is in as-equivalent-to-new and remanufacture product is in as-good-as-new condition. Lastly, availability of technology affects the technical aspect in product recovery. For instance, cleaning and machining technology in certainly important in remanufacturing option. Only use of the right machine tool onto the appropriate part dimension allows part remanufacturing. Overall, product recovery is viable if recovery technology is widely available and affordable.

2.2.5 Composite

A composite factor consists of more than one factor mentioned above. The common composite factor is eco-efficiency. The World Business Council for Sustainable Development (WBCSD) defines eco-efficiency as “the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle” [91]. However, in the era of rapid global change, the manufacturing sector is getting more competitive. New aspects that envision new dimension for the company might be considered in business strategy. Thereby, decision is getting complicated when more aspects are included in the decision problem. As such, multi-criteria decision analysis is required to solve the subject of composite aspect.

2.3 Decision Analysis Method

Decision analysis consists of theory, methodology and professional practice to address problem in a formal way. Decision analysis comprises various steps, methods and tools for classifying, describing and assessing the important aspects for a decision. The analytic methods deal with the situation largely depends on the decision environment, where the two primary decision environments are certainty and uncertainty. In the context of this thesis, all the work study covers on certainty environment. The decision could be judged by single aspect (single-criterion), as well as multiple aspects (multiple-criteria).

Decision making for single-criterion problem is straightforward. Basically, the decision is agreed upon the only favorable outcome. Cost or profit is the most common concern in business case as mentioned in [92, 93]. At times, some researchers convert any other factor into monetary value [72, 94]. As such decision method such as expected utility theory can be applied to well-form the representation of the decision. A certainty single-criterion decision environment hardly requires complicated theory or tool to solve the problem.

Decision analysis for multi-criteria problem involves multiple conflicting criteria that need to be evaluated in making decisions. Cost is often the main criteria, however, other measure like time is typically another criterion that is in conflict with the cost. In order to reduce the production time, more manpower or advance machine are needed, and thus resulted in higher investment cost.

A summary of decision analysis method is recorded in **Table 2-1**. The literature search was done by using Web of Science, Elsevier Science Direct and Google Scholar with the keywords include multi-criteria, product recovery and decision making. Narrowing down the search with these keywords helped in filter the search results more accurate. Literature survey conducted in this thesis reveals five categories of EoL product recovery decision methods, consisting of type of methods, field of applications, input information and outcome of the analysis. **Table 2-1** covered the analysis methods found in the literature, listing the study done from most recent to the past. The analyses are categorized into five generic groups:

- *Category 1*: Algebraic calculations in this category usually solve the problems by adding/ subtracting the value component or even simple multiplication/division is performed. Therefore, limited number of solutions is generated due to the exhaustive calculations. Moreover, the solutions analyzed using these methods could be incomplete.
- *Category 2*: Mathematical optimization deals with the problems of finding numerically minimums or maximums of a function. The solution generated from this method is totally based on measurable value, such as cost, time and carbon footprint, which usually the data are not available in development stage. This method had been widely studied in application from stationary to engine part. In order to estimate result as close proximity as the actual situation, the database for real time data is needed. Nevertheless, optimization cannot be done on unquantifiable factors, which is the drawback for this method.
- *Category 3*: Empirical method is a way of decision analysis based on collection of experimental data, knowledge or experience gain in analyzing past successful cases of product recovery. This is a useful method that could provide new solution without

wasting a lot of efforts to find the root cause. However, it is questionable for the validity of generalizing the result to other product. Thereby, user shall carefully define the scope and limitation before reference them for decision making.

- *Category 4*: Multi-criteria method is a comprehensive and close to realistic decision which considers all aspects of EoL recovery option selection. The decision method allows ranking of options or factors from most to least favorable (eg. AHP, PROMETHEE, ELECTRE, TOPSIS, etc.). These methods can analyze qualitative and quantitative factors at the same time. At times, decision maker has difficulty to make conclusion when there are non-dominated solutions. The non-dominated set has the property that is impossible to remove. Hence, multi-criteria method is the appropriate tool to handle such situation. For instance, use of utility theory to generate score for overall benefit. Including the ranking options and the generated score, a reliable and holistic approach of decision could be achieved.
- *Category 5*: Integrated approach refers to the analysis that combines several methods to solve a decision problem. For example, on top of applying any method mentioned above, product health monitoring is applied for more accurate analysis.

Table 2-1 Decision analysis methods for EoL product recovery option

Method	**Field of application**	**Input information**	**Outcome**
Category 1: Algebraic calculations			
Cost estimation (Xu et al., 2014) [92]	Automotive components	• Activity-based costing	• Optimized selection of EoL options
Value flow method (Kumar et at., 2007) [94]	Pen	• Value created by manufacturer	• EoL decision is made based on optimum net

		• Value consumed by consumer over the time • Value reclaimed by recovery	value
Recovery-conscious design method for complex products based on multi-criteria assessment of the recoverability (Mathieux et al., 2006) [95]	Television set	• Materials weight • Economic value • Environmental performance	• Quantify weight, economic and environmental impact recoverability indicator • Identify relevant and accurate product attributes for any recovery scenario
The Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency method (QWERTY/EE) (Huisman et al., 2004) [96]	Electronics	• Economic value • Environmental performance	• Select and rank improvement options of current and future EoL processing • Determine which options bring substantial environmental gain in relation to financial investment
Resource recovery via value cost model (Goggin et al., 2000) [97]	Smoke alarm	• Bill of material • Economic value • Recovery processes	• Determine the most appropriate level of recovery from cost and value perspective
Category 2: Mathematical optimization			

Hierarchical structure profit optimization with disassembly under environmental regulations (Lee et al., 2010) [98]	Computer mouse	• Product profit • Product revenue • Product cost	• Interactive method of EoL-option decision making and disassembly planning • Enable remanufacturing options to maximize product's EoL economic value
Recovery network of EoL product using multi-objective genetic algorithm (MOGA) (Farzad Dehghanian et al., 2009) [99]	Scrap tires	• Economic value • Social issues/impacts • Environmental performance • Technology type • Location of installed recycling plants	• Environmental and social impact of each EoL option was quantified • MOGA reaches Pareto-optimal solutions
Multi-objective evolutionary algorithm for product recovery optimization (Jun et al., 2007) [100]	Turbocharger	• Part recovery cost • Before-quality of part	• Analyzed result closed to Pareto optimal set. • Provide information for EoL process optimization
Interactive multiple objective decision making integrating Chebyshev norms and reference point method (Jin et al., 2007) [101]	Electronic product	• Activities based costing • Activities based processing time • Environmental impact evaluated by Environmentally weighted recycling quotes (EWRQ)	• Best satisfactory recycling plan
Revenue optimization method to evaluate EoL	Pen	• CAD assembly model	• Generate product recovery graph

option (Erdos at al., 2001) [102]		• Disassembly cost/revenue data • Evaluation rules	semi-automatically • Optimal disassembly plans that maximize revenue • Margin of allowed revenue reduction
Multi-objective method to maximize environmental impact and minimize deficit (Lee et al., 2001) [103]	Coffee maker	• Economic value • Environmental performance • Disassembly time	• Appropriate EoL option for components in product • EoL disassembly chart is generated for optimal stage
Category 3: Empirical method			
Evaluation for recycling via case-based reasoning (Shih et al., 2006) [104]	Electronics	• Wear-out life • Technology cycle • Design cycle • Disassembly time • Economic value	• Cost-benefit estimation • Determine appropriate EoL strategy based on most similar past case
Category 4: Multi-criteria method			
Multi-criteria matrix using AHP (Iakovou et al., 2009) [105]	Network terminal	• Market value of component • Environmental burden • Weight • Quantity of component in the product • Disassembly sequence	• Highest potential recovery benefits
Grey relation analysis (Chan, 2008) [106]	Consumer goods	• Economic factor • Social factor • Environmental factor • Ecology factor	• Optimal solutions can be obtained by taking the maximum Grey relation grades for product component and materials

Waste manement using Analytic Hierarchy Process (Staikos et al., 2007) [107]	Footwear	• Life cycle assessment for environmental impact • Cost benefit analysis for economic value • Technical feasibility, public opinion, market pressures and compliance for technical value	• Most appropriate EoL management option for a selected range of shoe types • Support material selection based on the recyclability factors
ELECTRE III method for outranking product EoL alternative (Burfadi et al., 2004) [108]	Vacuum cleaner	• Economic value • Environmental performance	• Best compromise EoL alternative
An end-of-life of product systems (AEOLOS) methodology (Kiritsis et al., 2003) [109]	Telephone	• Collection, storage and transport strategies • Technical, economic, social and legal life • Economic value • Environmental performance • Social	• Best compromise scenario for treating EoL product
Category 5: Integrated approach			
AHP-CBR evaluation system for EoL selection strategy (Ghazalli et al., 2010) [110]	Electronics	• Part processing time • Part cost	• Best EoL option for parts and components
Integrated approach through fuzzy	Materials management	• Environmental impact	• Recommend recycling method

membership function and AHP (Yu et al., 2000) [111]	for electronic products	performance • Product related cost • Recoverable materials	for each recycling bin • Suggest alternative recycling methods for each recycling bin • Compute total cost analysis for various recycling bins • Compute total environmental impact for all recycling plans

2.4 State-of-the-Art in Multi-criteria Decision Making for EoL Product Recovery

With the increasing cost of natural resources, manufacturers start to concern on the increasing material cost that directly affect to production cost. Thus, retrieving valuable parts and material from durable EoL product as input resources for production could be one of the best options for production cost saving. On the one hand, widespread social and political influences have raised the appetite for green products amongst manufacturers and their customers down the supply chain. New law requirements which govern responsible manufacturing, like the WEEE Directive in Europe and LPEUR in Japan, task these companies to go green by collecting and reprocessing returned products [112]. In view of manufacturing sector, rapid change of global economy has been pressing on manufacturer to response agilely and sustainable. Therefore, there is a need to consider these aspects in product recovery option selection.

Before the product recovery decision associated with multiple criteria is made, a thorough review on multi-criteria decision analysis method for EoL product recovery is conducted. In the review, a set of criteria for product recovery decision making is identified based on the objective and research questions considered in Chapter 1. With the set of criteria, research studies relevant to this area are evaluated. From the evaluation, the present research gap is further crystalized and will be addressed in this thesis.

2.4.1 Criteria for EoL Product Recovery

As mentioned in Chapter 1, the objective of this thesis is to develop decision support model to aid engineers in classifying the EoL product condition, but most importantly enlighten managers on optimal recovery option to match company's target. Based on the objective, decision analysis methods are reviewed above and multi-criteria method is specified for exhaustive evaluation. The purpose of establishing a set of criteria is to make sure the relevancy of existing methods so that a clear research gap in the current state-of-the-art can be improvised to encourage adoption of product recovery. The criteria for decision making in EoL product recovery is categorized into three main groups pertinent to the research questions pointed out in Chapter 1. The evaluation criteria are summarized in Table 2-2 and it will be explained in the subsequent sections.

2.4.1.1 Integrated Method

Integrated model addresses research question 1: *How to identify and quantify EoL product condition?* As explained above, manufacturers are facing difficulty in recovering EoL product efficiently with the lack of product information. It requires a longer process and effort to understand the returned product. In order to close the information gap, integrated method is necessary to consider in the research framework. Information of new manufacture product is accommodated as reference for identifying the condition of return

Table 2-2 Criteria generation for MCDM in EoL product recovery

Criteria		○	◔	◑	◕	●
Integrated Model	Time	Not considered	Considers only recovery time		Considers full life cycle time	Considers full life cycle time plus handling and delay
	Economic	Not considered	Considers only recovery operating cost (e.g. material, labor, energy)		Considers full recovery cost	Considers full life cycle cost
	Environmental	Not considered	Considers only recovery impact (e.g. energy)		Considers full recovery impact	Considers full life cycle impact
Conformity Decision Analysis	Consistency	Not considered manufacturing of new	Not considered manufacturing of new but comes with several recovery options		Considers several recovery options and benchmark with manufacture new	Above all; minimum and maximum threshold are explicitly modelled
	Accuracy	Top down model without clear input and output relationship	Bottom up model without consider sub-processes; provides relationship between input and output system		Bottom up model of sub-processes; provides relationship between input and output system	
	Unifying capability	Not considered	Not considered but possible (eg. eco-efficiency)		Considered with application of appropriate analysis method	
Adaptive Method	Implementation	Specially designed software	Adaptable on existing software packages that requires programming knowledge		Adaptable on basic software (eg. Microsoft Excel) that does not require programming knowledge	
	Application	Customized for specific product or industry	Analysis on single criterion for specific product or industry	Analysis on multiple criteria for specific product or industry	Analysis on multiple criteria with various decision options for specific product or industry	Analysis on multiple criteria with various decision options for any type of product or industry

product, and the resource consumption in manufacture new product is considered in the recovery option that going through manufacturing process. Moreover, the model is ready to take into account as many aspects as possible without building up the complication. The sub-criteria for evaluating the integrated model are time, economic and environmental. There is no preference order among the sub-criteria until the utility curve is set up (discussed in Chapter 6).

Time is the new consideration in product recovery, based on the literature review. Often, primitive manufacturing business has been focusing on lead time reduction in search of competitive advantage [113-116]. Similarly, the purpose of lean principles derived from the Japanese manufacturing industry indirectly gearing towards time minimization [117, 118]. As the result, the same aspect is appropriate to measure on product recovery in order to get the idea of recovery period. Undoubtedly, more detailed timing included in the model resultant more accurate estimation.

Economic benefit is the imperative measure in any business case. The method takes into account cradle-to-gate cost, from material extraction to end of manufacturing. Major cost components are operation cost, overhead, procurement and machine depreciation. In addition, the cost of sub-processes for manufacturing as well as recovery operation are modeled as close proximity as the real situation.

Minimizing environmental impact is evident alongside the enforcement of environmental regulations. As discussed previously, this aspect arises from social, politic and legislative compliance influence on green consumerism. Green consumerisms are among manufacturers and their customers down the supply chain. For this reason, measure on environmental impact caused by product recovery is inevitable. LCA for the product is carried out for all recovery options.

2.4.1.2 Conforming Decision Analysis

Next, conforming decision analysis is introduced to address the second research question: *How to make an accurate and consistent decision for selecting EoL product recovery option?* As mentioned, decision analysis could be simple if single criterion is considered in a decision problem. However, even a decision is made, the outcome might be subject to the decision maker's preference. Therefore, conforming decision analysis approach is proposed, firstly to ensure the consistency and accuracy of decision and secondly to eliminate the subjectivity on preference. All of the modeled values shall be benchmarked to the value of making new for the information of conformity. In other words, the outcome shall conform to the reference value (of making new) so that the decision will be always consistent. Moreover, taking into consideration the real data and modeling the options as close proximity as the real set up provide accurate conclusion. With the appropriate decision analysis method, the outcome of the analysis leads to justification of criteria weightage. Hence, subjectivity of criteria weight is eliminated. The sub-criteria for evaluating the analysis approach are consistency, accuracy and unifying capability.

The consistency of proposed method is evaluated with consideration of the product life cycle. The product life cycle for recover product starts from EoL product collection and re-process to the product back in use condition. Besides, varied recovery options are included in the analysis to provide a more comprehensive recovery solution. In order to assist a consistent solution, detailed computation on the minimum and maximum threshold values that inclusive optimistic and pessimistic of recovery situation are covered.

Accuracy is the next criterion, with consideration of the amount of information captured in the analysis. Breakdown of processes into sub-processes are required to determine actual consumption. As the lowest level of a process is scrutinized, more accurate the resource consumption calculation is. Then, the detailed calculations are summed as bottom up approach. During the calculation, input variables that relate to the outcome are identified.

Unifying capability is another key criterion in decision analysis. This criterion judges on the methods based on the capability of aggregating the score reasonably. Then, the aggregated scores are compared among the recovery options and the highest score is justified as the best EoL recovery option.

2.4.1.3 Adaptive Method

Adaptive method addresses the third research question: *How practical the developed method and model apply on different category of product for EoL product recovery decision making?* Often, rate of adoption for a method is not because of the quality of result but rather flexibility of the method. Complication and specialized skill involved are the obstacles in implementation. Moreover, application of method for specific sector or industry is detrimental to adoption effect. Thereby, implementation and application are identified as the judging criteria in the category of adaptive method.

The implementation criterion refers to the complication level and specialized skill involved in practicing a method. This criterion is particularly important as the intention of model or method development is to assist user generates rational solution. In ideal situation, creation of rational solution through the model or method implemented using software tool does not require customized software or specialized programming knowledge.

Lastly, the application criterion is judged by the diversified use. The method must be generic enough across the product categories and industry. Minor modification (depends on types of data) enables the application of method caters to other industry.

2.4.2 Evaluation of Existing Methods

After screening through the works related to decision making in EoL product recovery, six preceding methods that are closely relevant to the objective of this thesis are identified. The methods are thoroughly reviewed based on the set of criteria in previous section.

2.4.2.1 "Multicriteria Matrix" Methodological Framework

"Multicriteria Matrix" studied by E. Iakovou et al. is considering multi-aspect includes residual value, environmental burden, weight, quantity and disassembly of each component [105]. Determination of residual value, (component) weight and quantity are intuitive and tangible. On the other hand, LCA is conducted for environmental burden calculation. Ease of disassembly is identified based on disassembly process, time and necessary tool. The ranking ranges for the five aspects have to be defined manually, specifically for the product. After all, the criteria are ranked corresponding to the set of ranking range. In the study, the weighting factors are defined according to the manufacturer needs. Then, multicriteria score is calculated as the sum of the pairwise products of rankings multiplied by the parameters' weighting factors. This method considers more than two recovery options and the decision is made based on product level. However, decision making for component level can also be done. Finally, the solution leads to the amount of weight that is recoverable by certain recovery option. The methodology is separated into 2 phases. Phase 1 deals with the identification of most valuable component and Phase 2 handles the EoL management strategy for component level. The overall evaluation of the “Multicriteria Matrix” method by E.Iakovou et al. is summarized in **Table 2-3**.

Table 2-3 Evaluation score for the "Multicriteria Matrix" for EoL management of electronic products

Method		“Multicriteria Matrix”	
Main Author(s)		E.Iakovou et al.	
Institution		Aristotle University of Thessaloniki	
Criteria		**Description**	
Integrated model	Time	◔	Time is only considered in product disassembly
	Economic	○	Product recovery cost is not considered in the method
	Environmental	◕	Full LCA is conducted and comprehensive eco-indicators for environmental burden are considered
Conforming decision analysis	Consistency	◑	Performance of manufacturing of new product is not considered but the solution comes with several options
	Accuracy	◑	Some of the parameters conducted life cycle assessment
	Unifying capability	◕	Aggregation of score is viable but weighting factors subject to user input; result consistency is questionable
Adaptive method	Implementation	●	Implementable on spreadsheet with plotting capabilities
	Application	●	Able to apply on any product

2.4.2.2 Grey Relation Analysis (GRA) Approach

This research covers the multi-aspect of economic, social, environmental and ecological. The economic factor computes on EoL treatment value at component or material level. Social factor counts on damages to resources. Environmental factor regards to damages to human health and ecology factor reflects damages to ecosystem quality. The selection result of EoL options is evaluated by inter- and intra-criteria comparisons. And lastly, the optimal outcome is obtained by comparing the grey relational grades of different options based on the global GRA. A systematic flowchart for selection process of EoL option using GRA approach is presented in the study, however, details of data collection and computation is not provided. Further study on this approach might lead to solving the problem with uncertainty and incomplete information. The overall evaluation of GRA approach [106] by Chan is summarized in **Table 2-4**.

Table 2-4 Evaluation score for GRA approach

Method		Grey Relational Analysis (GRA)	
Main Author(s)		Chan	
Institution		The Hong Kong Polytechnic University	
Criteria		**Description**	
Integrated model	Time	○	Time is not considered in product recovery
	Economic	◑	Recovery operating cost is considered in the study
	Environmental	◑	Damages on human health is studied but not in detail
Conforming decision analysis	Consistency	◑	Performance of manufacturing of new product is not considered but the solution comes with several options
	Accuracy	◔	Top down model with no details of input
	Unifying capability	◕	Aggregation of score is viable; weight allocation is not studied; result consistency is questionable
Adaptive method	Implementation	●	Implementable on spreadsheet
	Application	●	Able to apply on any product

2.4.2.3 Analytic Hierarchy Process (AHP) Decision Making Model

AHP decision making model is constructed in this study to deal with quantitative and qualitative factors. The quantitative factors considered environmental and economic aspects and qualitative factor considered technical aspect. LCA is carried out in environmental aspect while cost benefit analysis (CBA) is done for quantifying economic impact. The environmental and economic calculations are explicit, performed by summation of all the values of sub-categories. The technical aspect consists of technical feasibility, public opinion, market pressures and compliance with legislation. However, no details of grounds for the collected data are mentioned in the work. Therefore, accuracy of the result remains inconclusive. Finally, the overall score for each recovery scenario is the sum of all factors with the product of decision variables weight and recovery scenario weight. The decision is made based on the highest composite weight. The overall evaluation of AHP technique [119] by Staikos is summarized in Table 2-5.

Table 2-5 Evaluation score for multiple criteria decision aid for selecting the best product end of life scenario

Method		Analytic Hierarchy Process (AHP)	
Main Author(s)		Staikos et al.	
Institution		Loughborough University	
Criteria		**Description**	
Integrated model	Time	○	Time is not considered in product recovery
	Economic	◑	Recovery operating cost is considered in the study
	Environmental	◕	Comprehensive list of environmental impact is considered in the study
Conforming decision analysis	Consistency	◑	Performance of manufacturing of new product is not considered but the solution comes with several options
	Accuracy	◕	Bottom up model for economic factor
	Unifying capability	●	Aggregation of score is viable; relative weight and composite weight are computed to quantify recovery scenario
Adaptive method	Implementation	●	Implementable on spreadsheet with plotting capabilities
	Application	●	Able to apply on any product

2.4.2.4 ELETRE III Method for Selecting the Best EoL Alternatives

This is a multiple criteria decision aid method developed in AEOLOS (An End-of-life of Product Systems) project. ELECTRE III method is implemented in the topic to handle imprecise and uncertain information about the evaluation of alternatives. Moreover, the method is not compensatory (eg. good score cannot be compensated by bad score). It allows incomparability and uses veto threshold in environmental and social impact assessment. Validation of the method using case study can be found in [120, 121]. The decision analysis method is part of the AEOLOS toolset, developed on a software platform. Thereby, special programming algorithm is needed in order to accomplish the methodology. Multiple aspects of criteria are considered in the method, which are environmental, economic and social. It takes into consideration the lifecycle function of the product. For example, the particulars of EoL scenario include various types of recovery options and logistic scenario covers the strategies for collection, storage and transport. Information at all level is important to evaluate economic, environmental, social and integrated impact. Besides, indifference threshold, preference threshold and veto threshold are the three parameters analyze in ELECTRE III method. The method ranks the best outcome based on particular aspect point of view. The overall evaluation of ELECTRE III method [120] by Bufardi et al. is summarized in **Table 2-6**.

Table 2-6 Evaluation score for selecting the best product end of life scenario

Method		ELECTRE III	
Main Author(s)		Bufardi et al.	
Institution		Swiss Federal Institute of Technology Lausanne	
Criteria		**Description**	
Integrated model	Time	○	Time is not considered in the study
	Economic	◑	Different factors of economic value are considered, but only recovery cost is counted
	Environmental	◕	Several environmental indicators are considered but no details on the product life cycle phase
Conforming decision analysis	Consistency	◑	Performance of manufacturing of new product is not considered but the solution comes with several options
	Accuracy	◑	Partially bottom up model, but no indication of relationship between input and output
	Unifying capability	◑	Aggregation of score is viable however no details of aggregating method is presented
Adaptive method	Implementation	◑	Solution is customized and programming skill is required
	Application	●	Able to apply on any product

2.4.2.5 Recovery Systems modelling and Indicator Calculation Leading to End-of-life-conscious Design (ReSICLED)

This is a product recovery-conscious method that enables scientific and quantitative assessment of the ability a product to be recovered. The method covers an in-depth study of recovery activity in the aspects of weight, economic and environmental. The ReSICLED method models the relationship between the main inputs and outputs, giving the functional performance of the process. For instance, the quantity of waste generated relates to the technical performance of the process, costs and benefits of the process relate to economic performance, and environmental impacts and benefits relates to environmental performance. The recovery decision is made with respect to the particular criterion; no aggregation of total score is required. The method can be easily practiced on spreadsheet (eg. Microsoft Excel) and widely applied on any product. The overall evaluation of ReSICLED method [95] by Mathieux is summarized in Table **2-7**.

Table 2-7 Evaluation score for ReSICLED

<table>
<tr><td colspan="2">Method</td><td colspan="2">ReSICLED</td></tr>
<tr><td colspan="2">Main Author(s)</td><td colspan="2">Mathieux et al.</td></tr>
<tr><td colspan="2">Institution</td><td colspan="2">Troyes University of Technology</td></tr>
<tr><td colspan="2">Criteria</td><td colspan="2">Description</td></tr>
<tr><td rowspan="3">Integrated model</td><td>Time</td><td>○</td><td>Time is not considered in product recovery</td></tr>
<tr><td>Economic</td><td>◕</td><td>Extensive recovery costs and benefits are included</td></tr>
<tr><td>Environmental</td><td>◕</td><td>Comprehensive quantitative assessment of overall environmental impact is considered</td></tr>
<tr><td rowspan="3">Conforming decision analysis</td><td>Consistency</td><td>◕</td><td>Performance of manufacturing of new product is not considered but the solution comes with several options</td></tr>
<tr><td>Accuracy</td><td>●</td><td>Bottom up model with the indication of input and output relationship</td></tr>
<tr><td>Unifying capability</td><td>○</td><td>No unifying capability is incorporated in the method</td></tr>
<tr><td rowspan="2">Adaptive method</td><td>Implementation</td><td>●</td><td>Implementable on spreadsheet</td></tr>
<tr><td>Application</td><td>●</td><td>Able to apply on any product</td></tr>
</table>

2.4.2.6 Integrated Method: AHP and Cost Benefit Analysis (CBA)

The work proposed a holistic approach for decision making on selection of EoL products recovery options, utilizing AHP and CBA integrated method. The methodology comprises 2 levels of decision making. The first level decision is made on selection of one of three recovery options (reuse, recycling and incineration). The second level decision is made on sub options found under each main option selected in first level.

Thereby, it reduces the solution space while maintaining quality solutions. The author justified selection of multi-criteria decision method and EoL recovery influencing factors extensively in the study. The overall evaluation of integrated approach [122] by Ziout et al is summarized in Table 2-8.

Table 2-8 Evaluation score for holistic approach decision making on selection of EoL products

Method		AHP and CBA	
Main Author(s)		Ziout et al.	
Institution		University of Windsor	
Criteria		**Description**	
Integrated model	Time	○	Time is not considered in product recovery
	Economic	◕	Recovery operating cost is considered in the study
	Environmental	◕	Comprehensive list of environmental impact is considered in the study
Conforming decision analysis	Consistency	●	Performance of manufacturing of new product is not considered but the solution comes with several options
	Accuracy	●	Bottom up model for economic factor
	Unifying capability	●	Aggregation of score is possible with the product of alternative weight and influencing factors global weight
Adaptive method	Implementation	◕	Implementable on spreadsheet is possible but tedious, otherwise specialized soft ware is needed
	Application	●	Able to apply on any product

2.4.3 Comparison of Evaluation Results

The evaluation of existing methods based on the criteria for decision making in product recovery fulfills two main objectives. Firstly, the individual scores of the methods are compared to observe the strengths and short comings. Complementary work could be done based on the existing methods to empower a reliable decision analysis method in EoL product recovery selection. Secondly, the average scores of the criteria fill in the information on establish work in particular area. Meanwhile, highlight the loose track in decision making support model in EoL product recovery. This loose track is the gap that weakly links the current state-of-the-art and the final goal that is to be achieved in the thesis. **Table 2-9** is the summarized results of the evaluation methods presented in previous section.

Table 2-9 Summary of evaluation of research approaches based on the criteria for multi-criteria decision making for EoL product recovery

Decision Making Method		Multicriteria Matrix	GRA	AHP	ELECTRE III	ReSICLED	AHP & CBA	**Average Criterion Score**
Integrated Model	Time	◔	○	○	○	○	○	0.04
	Economic	○	◑	◑	◑	◕	◕	0.50
	Environmental	◕	◑	◕	◕	◕	◕	0.71
Conforming Decision Analysis	Consistency	◑	◑	◑	◑	◑	◑	0.50
	Accuracy	◑	◔	◕	◑	●	●	0.63
	Unifying capability	◕	◕	●	◑	○	●	0.58
Adaptive Method	Implementation	●	●	●	◑	●	◕	0.79
	Application	●	●	●	●	●	●	1
Average Method Score		0.59	0.56	0.53	0.53	0.63	0.72	0.59

Score	
○	0
◔	0.25
◑	0.50
◕	0.75
●	1

From the table above, it clearly shows that none of the existing method presents a high degree of consistency and accuracy decision in regards to time, economic and environmental aspects. Among the methods, the integrated approach (AHP & CBA) come the closest to the methodology proposed in this thesis. The main shortcoming is lack of time aspect consideration in the solution, which is an important indicator to justify how long an EoL product can be recovered using particular recovery option. It is followed by the consistency of the solution. However, the key strength of the method is the influencing factors detail that provides a more comprehensive solution. The next closer solution method is ReSICLED, which is a systematic and all-rounded consideration within the influencing factors. However, the recovery decision is made with respect to particular criterion.

When average scores are compared across the criterion, the existing methods show uncommonness in considering time aspect as influencing factor in the product recovery decision problem. Also, none of the method refers to manufacturing data in EoL product recovery decision analysis. The sub-criteria of economic, consistency, unifying capability and accuracy are relatively lower. On the other hand, the compiled result shows that environmental aspect is well considered in existing EoL product recovery decision making methods. In general, all the methods have high degree of flexibility, which the methods are applicable on any other product. This is because the quality of research approach is eventually reckoned by the level of proliferation in industry practice.

2.5 Research Gaps

After the evaluation on existing methods related to decision analysis in EoL product recovery, criterion with the lowest scores are identified as the research gap that to be solved in the thesis. The distinct gaps for providing a reliable solution are consideration of time aspect, consistency of the result, unifying capability and accuracy of the result.

As mentioned previously, time is an important indicator that measures the efficiency of the process or recovery solution. Indirectly, this can be used as the feedback information to product or even process design to improve the condition.

Oftentimes, the solution obtained has the best benefits among the options. Benchmark of the recovery resource consumption to the resource consumed in manufacturing new is neglected in the existing method. The compared results inform the extension of acquired resources. For example, if an advanced technology able to recover a part with three times the cost of manufacturing of new, common sense tells us that this is not a reasonable solution. In addition, some of the methods make decision based on weighting, which is also referred as importance. There is lack of classification on the level of acceptance before the decision is made. In other words, no acceptance standard to judge how good or bad is the resource consumption in particular recovery option. Thereby, there is a need to introduce the minimum and maximum threshold values to set the boundary for acceptance.

In order to survive in the competitive and fast changing world, there are more factors of concern in the company business strategy. All-rounded solution is required for the business plan. As the result, an analysis method with fair reasoning and capability of unifying the factors value is necessary.

Last but not least, decision analysis is overtaxed if it does not provide an accurate result. The study breaks a particular process in detail, therefore more accurate information can be obtained. Utilizing of the accurate information in decision analysis resulted in accurate outcome.

2.6 Summary

In this chapter, the status of research on product recovery is presented, which the concept of product recovery comes from product life cycle management. With product recovery in mind, types of product recovery option are introduced. Following the recovery option introduction, important aspects that affect decision making in product recovery is discussed. Deciding on the recovery option with multiple aspects is challenging without apprehend the analysis method. Thereby, decision analysis method is explained and state-of-the-art of the decision method is reviewed critically to know the status of study done. In the critical review, a set of criteria relevant to decision making in EoL product recovery was identified. The set of criteria was then used as the reference to evaluate the existing method related to decision making method in EoL product recovery. Six existing methods that are closely related to the scope of thesis are evaluated. From the evaluation, it clearly shows that the existing methods do not adequately address the problems in decision making in product recovery, particularly to achieve a reliable solution. The shortcomings of the methods are concluded in the research gap, which will be addressed in the thesis work.

CHAPTER 3

Research Framework

This chapter presents the development of generic EoL product management framework. The framework incorporates product life cycle concept, which is designed for original equipment manufacturer (OEM) as well as third party recycler to enable them manage the resources at product end-of-life (EoL) phase more efficiently. This is followed by introducing research framework. The proposed framework in this chapter addresses part of the first research question on the general process to characterize EoL product condition.

3.1 Product Recovery Framework

Framework in Figure 3-1 shows the overview of product recovery, where illustrating the big picture of process, information and material flow [123, 124]. The overall framework is important for developing the research framework. With the comprehensive knowledge, research direction can be developed accordingly to the requirement. The overall framework is particularly appropriate for the OEM where all information are readily available. On the other hand, the research framework in grey shading boundary is useful for third party recycler.

Product recovery management starts from comprehending company goal followed by knowing the company’s target. Consideration of these two steps in the framework informs a company’s direction, so that the company targets bring about requirement for analysis. Thus, the outcome of the analysis can reflect the correspondence between decision and company's goal. The framework can be generally applied onto any product.

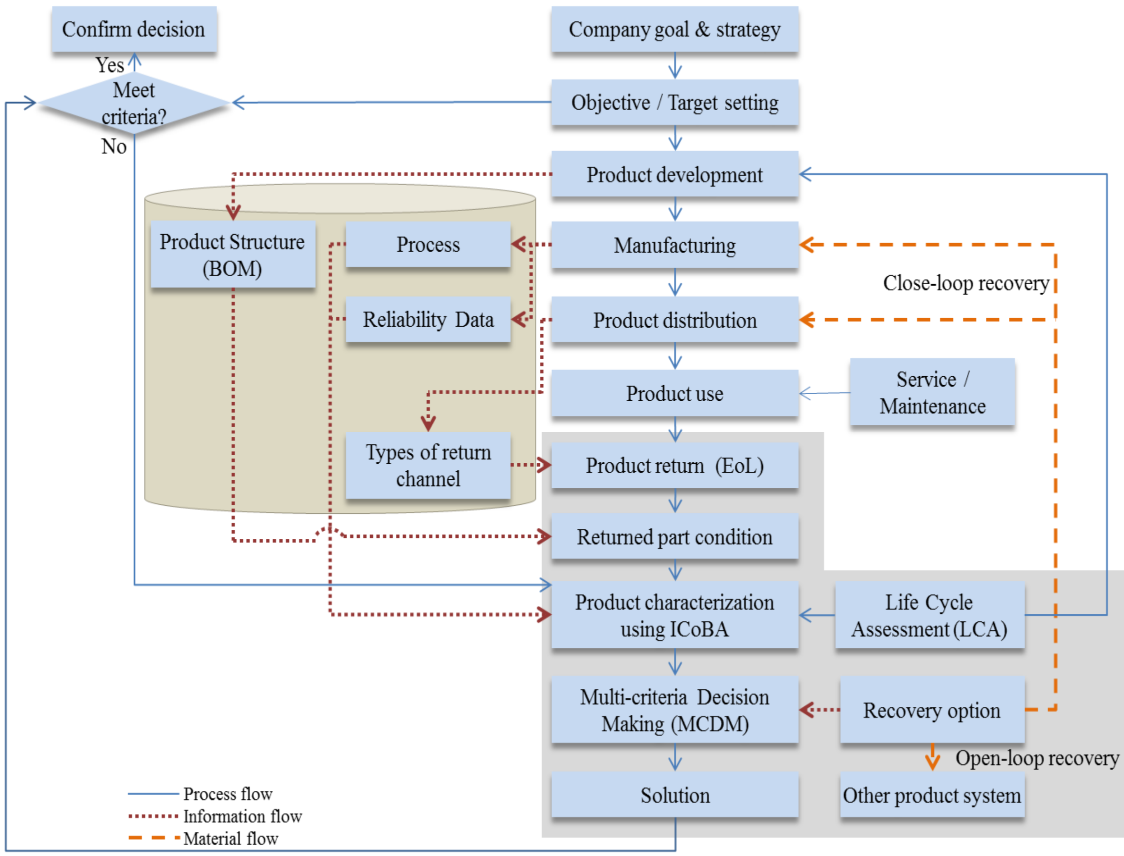


Figure 3-1 Product recovery framework

Next, product development in the framework might be going through conceptualization, prototype production and prototype evaluation. The processes are repeated until the prototype reaches standard of quality required. However, there is a recent trend on increasing awareness of industry finding ways to produce environmentally friendly products and manufacturing processes, and also individuals and families anticipate in green lifestyles. In order to reach market wants, manufacturer has increased attention on product development that follows the environmental guidelines to benchmark the environmental performance. Thereby, life cycle assessment (LCA) is introduced to perform valuation to conclude whether a product or process is environmentally friendly.

After the product completed developing, information of the product that consists of multiple modules that are made up of different parts, components and materials used are consolidated as bill of materials (BOM) list. The BOM list contains the information of part name, part number, code of drawing for the parts and modules, and even cost. It gives an overall view on the hierarchical relationships of product structure between modules and parts. Also, it provides an indication of which parts are manufactured in the particular production system and which are procured from suppliers. This information not only needed in product manufacturing, it is also essential for product recovery in later stage. The BOM information is useful for recovery department manager in such a way that quick decision can be done based on the readily available knowledge.

Based on the product specifications and product manufacturing plans determined in product development phase, manufacturing line that produces commercial prototype is built. Modifications and improvements of the process are allowed in the manufacturing line to make the production as efficient as possible. Then, the completed products are tested to assure the reliability. Products that pass the inspection are packed and delivered to customer. Cast iron part is used in the thesis to illustrate the details in manufacturing process and reliability analysis. Cast iron has been widely used and become an engineering material with a wide range of applications. For example the transportation industry, heavy equipment, household appliances and sports equipment. Figure 3-2 shows the sand casting (also known as metal/iron casting) process, which the steps in each process are used for calculating time, cost and environmental performance in the later stage.

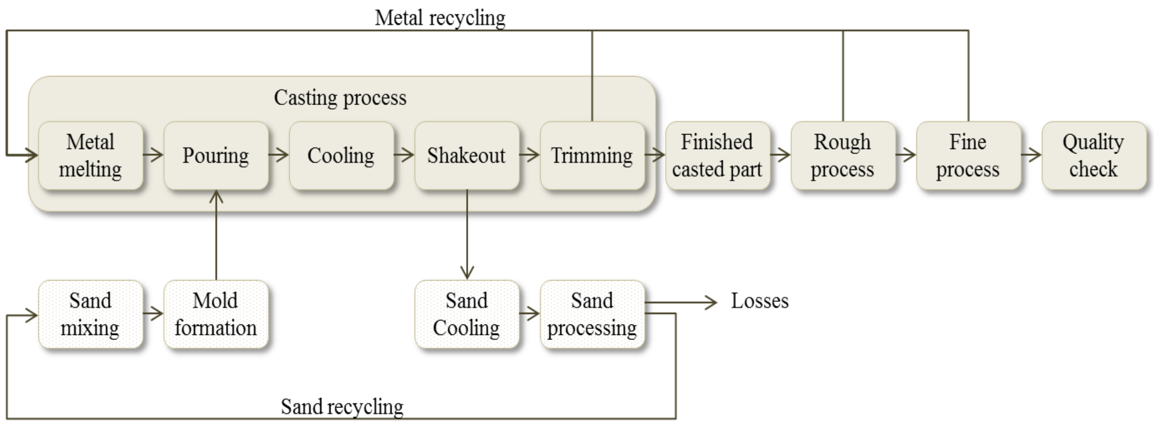


Figure 3-2 Process of cast iron

After the product is produced and priced, it is distributed to the market place. The information of product distribution is important for product recovery department to keep track where is the returned product from. Product usage is usually the longest stage (in term of time) in the product life cycle. In some case, the products require frequent service or maintenance in order to keep the product functions orderly. The following steps will be covered in research framework, which the main focus is making optimal decision in EoL product recovery option selection.

The recovery option is broadly classified into two categories: close-loop recycling and open-loop recycling (shows in Figure 3-3). Close-loop recycling is a process that takes the products at the end-of-life stage and converts them into the same product. The close-loop recycling includes the options of reuse, remanufacture and recycle, which reuse of the same product is an obvious close-loop recycling practice. Remanufacture and recycle could happen in both categories. Part that is remanufactured to the same dimension and function, also recycled material used in place of virgin inputs to manufacture the identical product are considered as close-loop recycling. On the other hand, part that is remanufactured in different dimension or change of function as well as recycled materials feed in other product system are considered as open-loop recycling. And obviously, product that is made of raw materials and disposed at the end-of-life stage is definitely an open-loop recycling process. However, both categories provide benefit in terms of cost, time and environmental impact reduction if product B system is getting resources from EoL product recovery. This is because it offsets a portion of the resources spent in upstream such as raw material extraction, material process and transport of virgin materials. With the assumption of product take-back regulation is enforced, OEMs are indirectly forced to deal with close-loop recycling. Therefore, an informed decision making method is required to justify the best option.

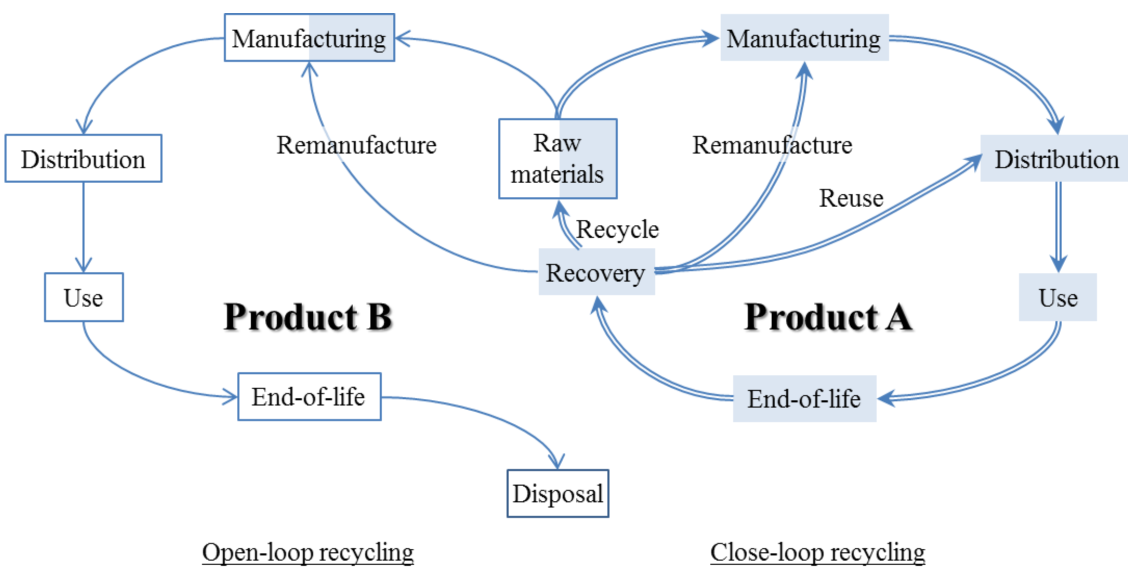


Figure 3-3 Overview of open- and close-loop recycling

3.2 Methodology for EoL Product Recovery Decision Making

Methodology for EoL product recovery decision making (in Figure 3-4) is proposed to achieve the thesis objective. The approach is applicable to OEM as well as third party recycler, with the premise of related information is given to the third party recycler. The study starts with identifying EoL product return by recognizing the source of returns. The types of return channel proffer the knowledge for estimating part condition. With the input of product structure from BOM list, it further determines the condition of EoL part. Then, the part is further characterized with the application of LCA method using Inference Conformity Based Analysis (ICoBA), which will be explained in Chapter 4. Reuse, remanufacturing and recycle are the recovery options in this study. With the consideration of multiple criteria on various recovery options, decision making analysis will be carried out to provide the optimal result. The detail of decision analysis will be presented in Chapter 5.

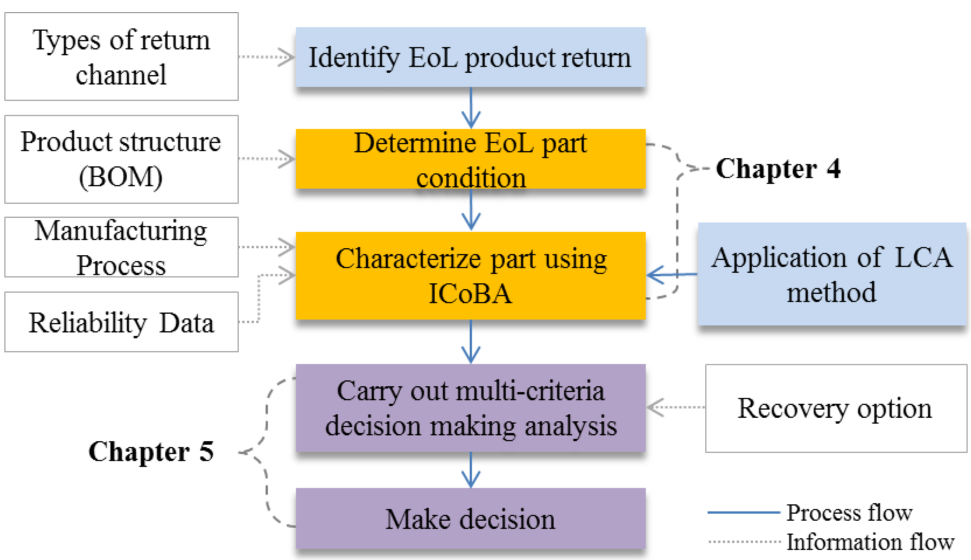


Figure 3-4 Methodology for EoL product recovery decision making

3.2.1 Identify EoL Product Return

After the product has been used for a period of time, the product is unwanted, depend on the user behavior. In this study, unwanted product is also known as end-of-life (EoL) product, which the product no longer fulfills the needs. With the assumption of take-back regulation is enforced, the EoL product has to be returned to the manufacturer by all means. The types of product return are coming from production rejects, supply chain return, end-of-lease return, warranty return and consumer return [125]. Figure 3-5 shows the example of categorization of product distribution and type of product return.

- *Production reject* is the defective part / product that might be caused by errors in manufacturing process, handling or assembly. Thereby, the erroneous part is not suitable for further assembly into product.
- *Supply chain return* is the unsold products returned from wholesaler or retailer. It might be obsolescence products due to mistake in sales estimation resulted in excess purchase or shipment.
- *End-of-lease return* refers to the returning of leased product when the lease schedule is expired. At the end of the leasing period, the old equipment is often replaced by a new unit.
- *Warranty return* is the product returned by consumers against defects in material and workmanship or fail units within a certain period of time specified by manufacturer or retailer.
- *Consumer return* is mainly refers to end of product usage. Consumers might return the old unit as trade-in when they purchase a new unit for replacement. In other case, consumer sells it as raw material to the third party waste recycler.

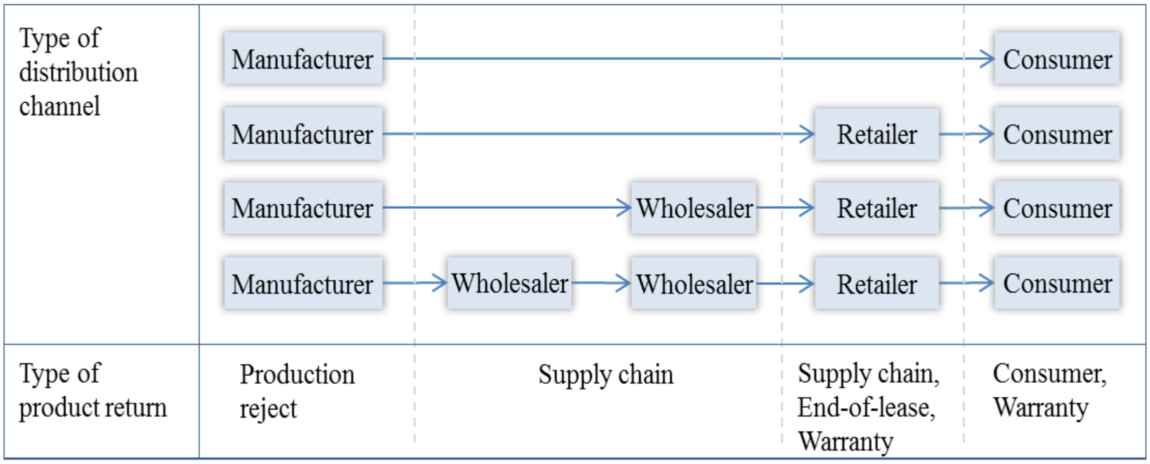


Figure 3-5 Relationship between distribution channel and type of product return for consumer product

3.2.2 Determination of EoL Part Condition

At the point of product return, part condition is determined using the process flow shows in Figure 3-6. When a product is returned, the product model is first identified, followed by identify the date of return and sort out the product based on the types of return channel. The return channels include production reject, supply chain return, end-of-lease return, warranty return and consumer return, where the condition of the returned product/part from different channel will be explained subsequently. After the product is returned, it is dismantled and valuable parts for recovery are identified based on the BOM list. The part that is returned for recovery has to verify for its origin and model. In this case, the proposed method is designed for recovering the original part. After the part has been verified, engineer shall refer the database to find out date of manufacture to determine the part age. The age of product is an important indicator to judge part's reusability. For a used part, if the age has over the designed life, where the reliability of the part is not covered in product development phase, the part is not appropriate for reuse.

Otherwise, part condition (remaining useful life) shall be determined based on the available historical or statistic data saved in product development phase.

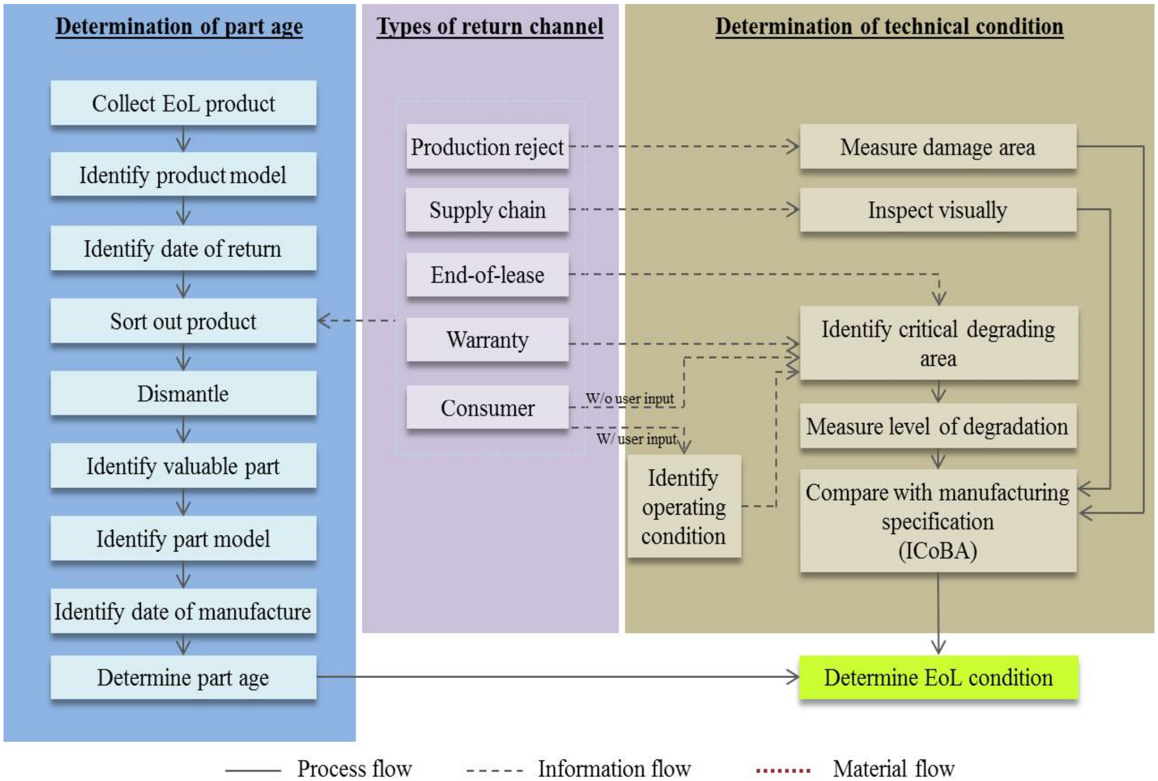


Figure 3-6 Process flow for EoL part condition determination

The returned product condition is further confirmed based on the types of return. The part/product is mainly categorized in unused, predictable and unpredictable status, which the status are generalized from the information of distribution channel and type of return accordingly (shows in Figure 3-7). With the organized information, engineer could observe the part status promptly and quantify the part more accurately.

- *Unused (with error)* condition is typically caused by inconsistent manufacturing process that resulted in inaccurate part dimension. Also, the defective unused part could be due to error in assembly or destructive dismantling if the product is malfunction.

- *Unused (new)* condition, on the other hand is referring to the part that does not affected by product assembly/disassembly activities. Moreover, products that return from supply chain (distributor) are mainly in new condition with remaining shelf life.
- *Predictable* condition for warranty return product is possible since the product has been used in a limited timeframe. The condition can be predicted with reference to the historical data on failure rates of similar products in product development. Part in leased product is somehow predictable because usually the leasing service comes with maintenance service in the contract. Up-to-date part information is recorded if replacement or repairing is done during product maintenance. However, the complete identity of the product could not be confirmed as there is a mixture of old and new parts in the reconditioned equipment. Therefore, it is rather difficult to accurately predict overall product performance.
- *Unpredictable* condition is identified from the consumer returns which there are unknown operating condition and environment during usage stage. Thereby, the condition of the product could have large variation. For instance, the condition of a 5-year old machine could be better than a similar 2-year old machine under different operating frequency. However, some analysis can be done to quantify condition of the part from consumer returns.

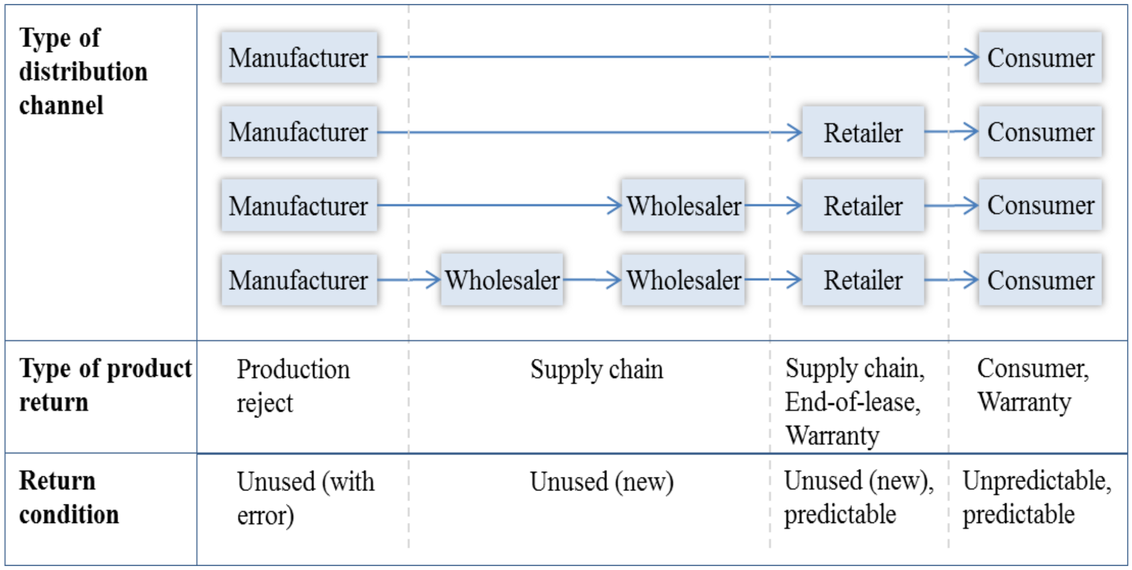


Figure 3-7 Classification of return part condition with type of return (consumer) product information

From the assessment, the part used life (getting from returning date minus manufacturing date) is proposed to correlate with the type of return to substantiate the part condition more precisely. This is because the condition of a returned part does not necessarily degrade along with used life, as show in Figure 3-8. For instance, condition of the part that is rejected from production line is new however faulty (shown as dot in Figure 3-9). Thus, engineer measures the damage area, compare to the manufacturing specification, and then make conclusion for the part condition. Part returns from supply chain is most probably in perfect condition regardless of used life (shown as circle in Figure 3-9), however, visual inspection is necessary to reassure the condition is up to manufacturing specification. If engineer were to determine the part condition without knowing the source of part, based on the received and manufactured date, he would misinterpret the part as used part. Similarly, knowing the return channel, the trend of end-of-lease product could be better predicted as described in the dashed line in Figure 3-9.

As for the part from warranty return, the product mechanism would have gone awry at any time before the guaranteed useful life, shown as dotted line in Figure 3-9. Part from warranty return needs to identify for the critical degrading area, followed by measuring the degradation. Then, it is compared to the manufacturing specification to confirm the part condition. Lastly, the part condition returned from consumer is random and unpredictable. For instance, part that is gotten from product ‘A’ used for short period of time but high frequency might function worse than product ‘B’ used with low frequency for longer time (shown as cross in Figure 3-9). If there is usage information provided by user, the product operating condition is known, thus it simplifies the process to identify the critical degrading area and further process to determine part condition. Otherwise, engineer requires longer time and effort to conclude the part condition.

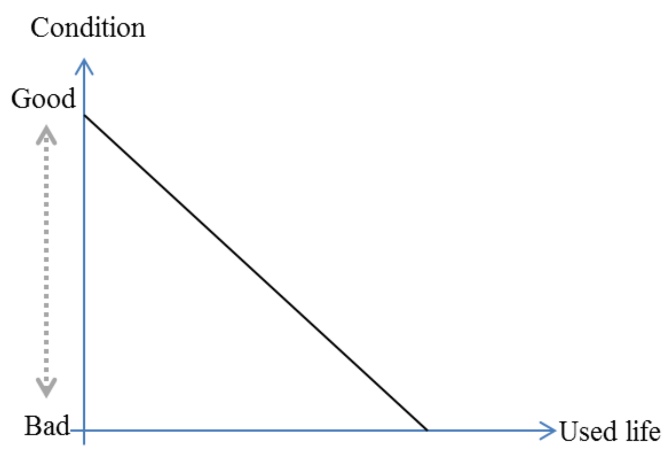


Figure 3-8 Part degradation trend under consistent usage condition

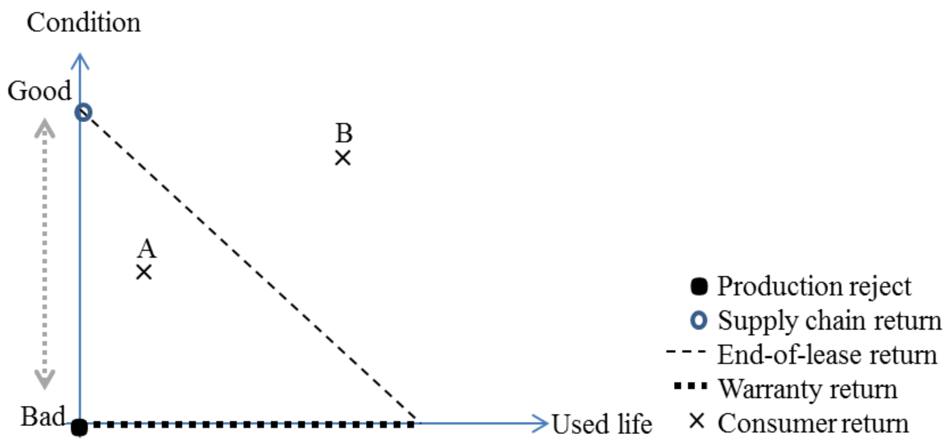


Figure 3-9 Part degradation trend based on type of product return

3.2.3 Application of Life Cycle Assessment (LCA) Method

According to industrial ecology, the life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying, quantifying and assessing the impact of energy and material usage and environmental releases. The International Standard Organization (ISO 14040: 1997) defines LCA as a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product throughout its lifecycle [126]. It looks at the system prospective of a product, which can be used as a tool to help companies understand the environmental impacts associated with their core business. The result of LCA is not to arrive at quantitative figure, but rather to provide important inputs to a broader business strategic planning. The assessment able to identify the potential area for improvement, such as improves efficiency in process or even enriches innovation on product design.

In this study, LCA is implemented mainly to identify the major contributor of environmental impacts in processes, resources and systems. Secondly, manufacturer performs LCA to compare different options with the goal of minimizing environmental impact. And lastly, LCA is being used as a tool to provide guidance in one of the criteria for decision making.

There are three approaches for assessing industrial systems, namely "Cradle- to-Grave", "Cradle- to-Gate" and "Cradle to Cradle". "Cradle-to-Grave" is a full LCA assessment from material acquisition (cradle) to use phase to disposal phase (grave). In this approach, all inputs and outputs from all phases of life cycle are considered. "Cradle-to-gate" is a partial life cycle assessment from resources acquisition (cradle) to factory door (gate) before the product is distributed. The benefit of this approach allows LCA accumulate all the impacts from resources being purchased by facility, plus the impact for transportation and processes. It would be easily generate the impact values for the product. The third approach is "Cradle-to-Cradle", also known as closed loop production. It is relatively similar to "Cradle- to-Grave" approach, however, the end-of-life (EoL) disposal step for the product is replaced with recovery treatment such as reuse, remanufacture, recycling process and so on.

Figure 3-10 shows the phases of a product life cycle (PLC), where the PLC starts with raw material acquisition to material production, product manufacturing, distribution, use and end with disposal. For a consumer product, raw material acquisition would include crude oil processing into polymers that makes plastics, metal is extracted from mineral ores to make machine part, and timber is harvested to process into lumber and paper for packaging. Moreover, process of raw material such as metal must undergo reduction to free the metal which happens in material production stage. After this, the material moves to the product manufacturing stage where the plastics are made into housing, metals are made into parts and cardboard is made into packaging box. The finished products are then distributed to retailers or shops. The products are used for a period of time and finally disposed of at the end of use. This is the primitive open loop product life cycle manner, where the material value is eventually lost.

In order to better preserve the resources from EoL product, product recovery is introduced. The recovery treatment can occur in several ways, namely reuse, remanufacture and recycle. A product can be reused, which it happens when the product is used for only short period of time and being replaced by a newer version of product. As for the malfunction yet high value product, it could be sent to product remanufacture, where the part could re-machine into like new product. Finally, the low value parts might be recycled to materials, and then they are fed as a raw material for another product manufacturing process.

As seen the diagram in Figure 3-10, along the product life cycle stages, transportation is required to transfer materials and products. And so, raw materials and energy are the input force to the life cycle system. At the same time, activities along the PLC stage produce waste and emissions. These outputs pose potential negative impacts to the environment. The common categories of negative impacts include global warming, (air, water, land) toxicity, ozone layer depletion, acid rain, minerals and fossil fuel depletion.

As a consequence, LCA is the appropriate technique to assess the environmental aspects and potential burdens associate with making product. It compiles the relevant input energy and material, and the output releases. Subsequently, it evaluates the environmental impacts based on the identified inputs and outputs. Thereafter, the analysis outcomes could aid in making more informed decision.

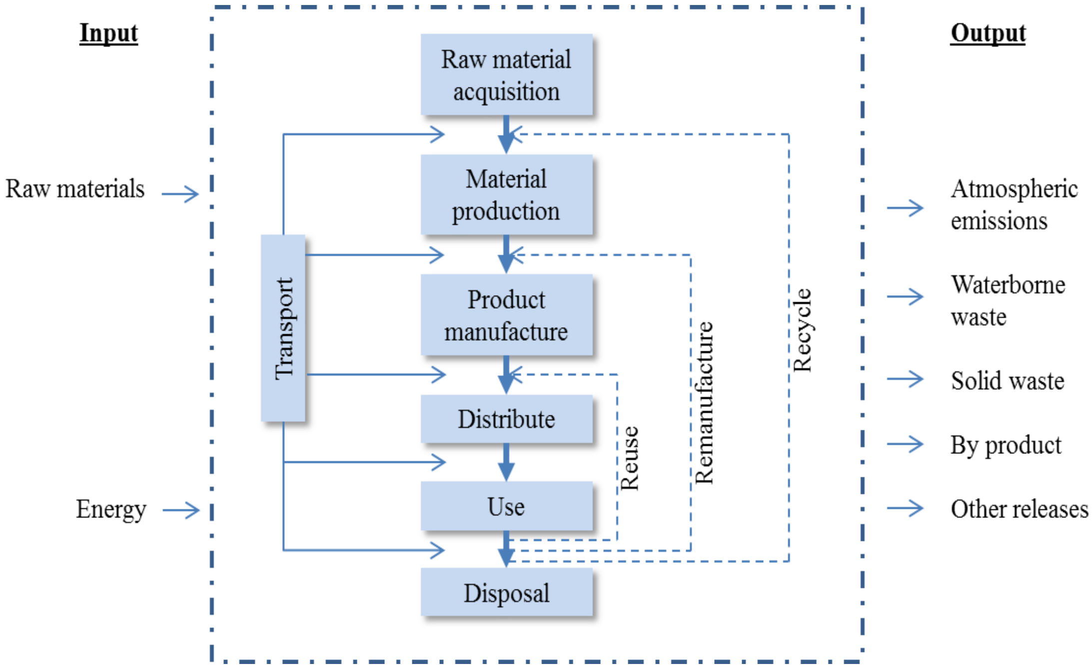


Figure 3-10 Product life cycle stages and the relationships

The LCA methodology is a systematic approach shows in Figure 3-11 as follow. It consists of four phases, which cover in ISO14040 [127] and ISO 14044 [128].

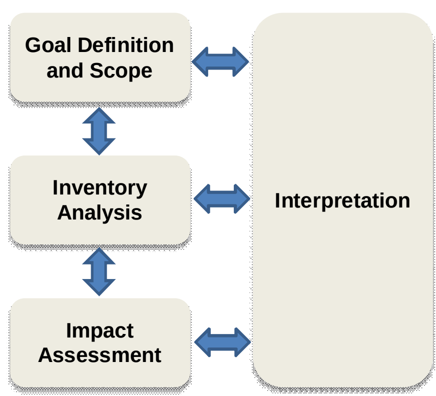


Figure 3-11 LCA framework

Phase 1: Goal definition and scope

The goal and scope define and describe the product, process or activity, which the level of specificity to determine the boundaries of study is of prime important. The product being studied has to be specific whether it is the particular product of the particular plant or the industrial average. As different plant could have different emission levels based on different processes. The specificity of product directs the level of data that need to be collected.

Phase 2: Inventory analysis

In inventory analysis, all the inputs and outputs data relevant to the system under studied are collected. In this phase, collection of necessary data is to meet the defined goal. As a result, the level of accuracy in data collection is highly sensitive to the scope of application. For instance, to drive public policy, high certainty of data is essential. On the other hand, to make decision within a firm, data collected could be reasonable estimate. There are two types of data, which are primary data and secondary data.

- Primary data are the process-specific and facility-specific data. These data are particularly from the operation within given facilities. It is the most representative type of data, however, one has to resort to secondary data if the primary data is not readily available (eg. data from upstream process).
- Secondary data are the less accurate data, which the data is calculated from equations. The data could be also from the scaled up laboratory data.

Phase 3: Impact assessment

In phase 3, it translates the environmental burdens identified in inventory analysis into related environmental impacts. In order to carry out impact assessment, one needs to go through the steps: classification, characterization, normalization and valuation.

- Classification involves the aggregation of environmental burdens to certain categories of potential impacts on human and social ecology. The environmental impacts consider climate change, ozone depletion, human toxicity, acidification, eutrophication, ecotoxicity, non-renewable resource depletion and so on.

- Characterization requires quantification of the impact of interest relative to a reference matter. For example, global warming potential related to carbon emission. Determination of carbon footprint (carbon emission) of the product life cycle relates the potential impacts.
- Normalization normalized the impacts with respect to the total emissions in certain area over a period of time. It helps to identify the regional or global environmental impacts.
- Valuation (or weighting) refers to assignment of weighting to the impacts that indicates its relative importance. Lastly, the environmental impacts are cumulated into a single environmental impact function.

Phase 4: Interpretation

Interpretation is the last phase in LCA, which it should deliver results, explain limitations and provide recommendations. The results need to be interpreted on the same basis, so that comparison can be made in terms of equal stage or fashion. For instance, to compare carbon emission saving from remanufacturing versus recycling, the basis should be the identical finished product.

3.2.4 Implementation of ICoBA

Inference conformity based analysis (ICoBA) is a method to justify whether the EoL part condition is in accord with the prevailing quality. The method will be applied in two stages in the research framework. In first stage, ICoBA is carried out during determination of EoL part condition. It is applied to verify the conformance of the EoL part condition to the newly manufactured part specification. The resulted divergence of the EoL part quality/condition indicates the possible recovery option. Thus, characteristic based values depend on the recovery option can be generated for further analysis. In the second stage, ICoBA is applied in the decision analysis where the information of manufacturing new part is used as the reference point. The estimated EoL part values that are incongruous with the reference value reveal the performance of certain attribute (characteristic) in particular recovery option. ICoBA analysis is done on every returned part that is identified for recovery. In this study, the decision is made based on three attributes (characteristics): cost, time and environmental impact.

- *Cost* consists of operation, overhead, procurement and machine depreciation in the manufacturing and recovery process.
- *Environmental impact* refers to GHG emission from manufacturing and recovery activities.
- *Time* refers to the time consumption for manufacturing and recovery activities.

In order to quantify the criteria, LCA is applied for cost analysis, time analysis and environmental impact assessment. The system boundary considered in the study is shown in Figure 3-12.

The product life cycle is classified in material phase and product phase, where the ‘product’ refers to cast iron part in this study. All calculation and comparison are done at end of the product phase so that evaluation is done on the same basis. However, impact on distribution, use and re-distribution are omitted with the assumption of the effect has been cancelled out across all options. The product life cycle stages include:

- *Procurement*: Raw materials that make cast iron part are procured from suppliers.
- *Manufacturing*: Manufacturing of the part, reliability testing, structural and flaw detection take place in this stage.

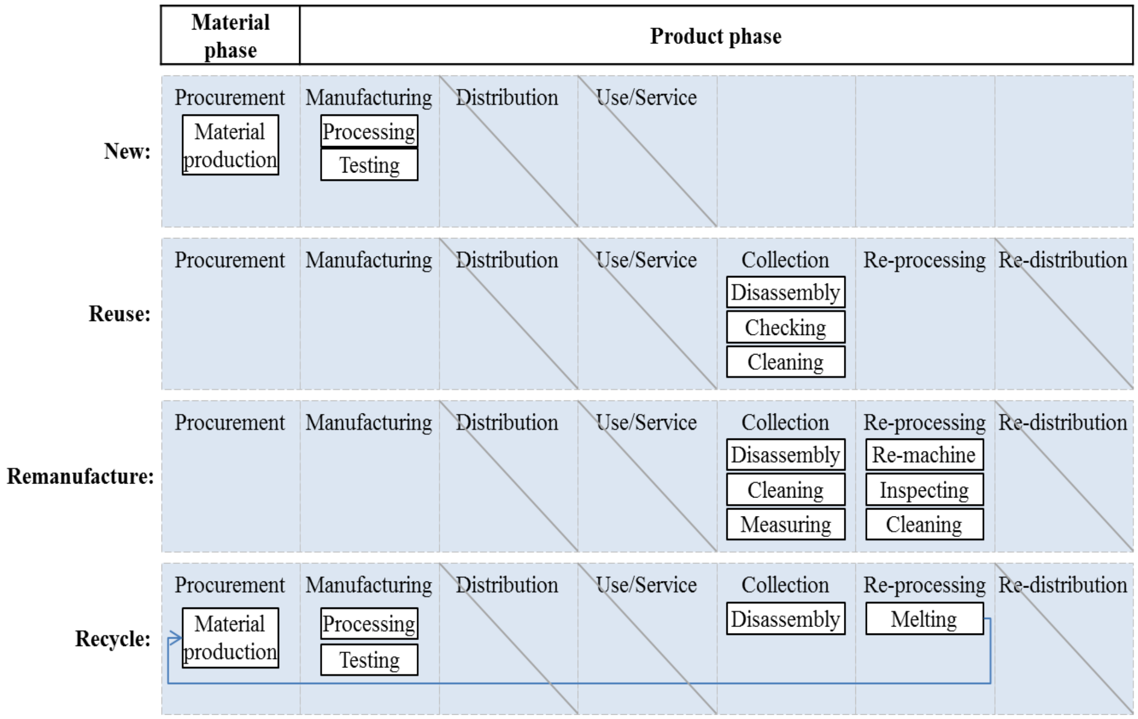


Figure 3-12 System boundary for new and recovery product

- *Distribution*: After multiple parts are assembled into final product, the product is packed and distributed to customers.
- *Use/service*: The parts are assembled into product and sold to customers. Assembly and disassemble may occur in this stage for product service.
- *Collection*: At the point of return, the product is disassembled into parts. The parts are checked and cleaned for reuse. Otherwise, the parts are opted for remanufacture, where parts condition determination is required to verify cost of reprocessing.

- *Re-processing*: There is no re-processing action required in part reuse option. However, parts that need to be remanufactured are going through re-machine, inspection and cleaning before the parts are re-distributed. On the other hand, parts with low value are going through melting process to recover the material.
- *Re-distribution*: Parts that are recovered from returned product are in their final form for re-distribution. The parts could be sold as standalone component in second hand market or sold the recycled material to other manufacturer. However, cost, time consumption and environmental impact associated in this stage are excluded for all options.

With the clear system boundary setting, overall cost calculation that consist of activity based costing for operation, overhead, procurement and machine depreciation can be done. It gives a clear picture on particular steps in the PCL stages so that computing the activity based time consumption is straightforward. Figure 3-13 shows sub-criteria that are related to the main criteria, which is broadly classified into cost and environmental components. Grouping the criteria is particularly helpful in scrutiny whether the set of criteria is right adapted to the problem. Another advantage of grouping the criteria is it aids in visualizing the emergence higher level affair.

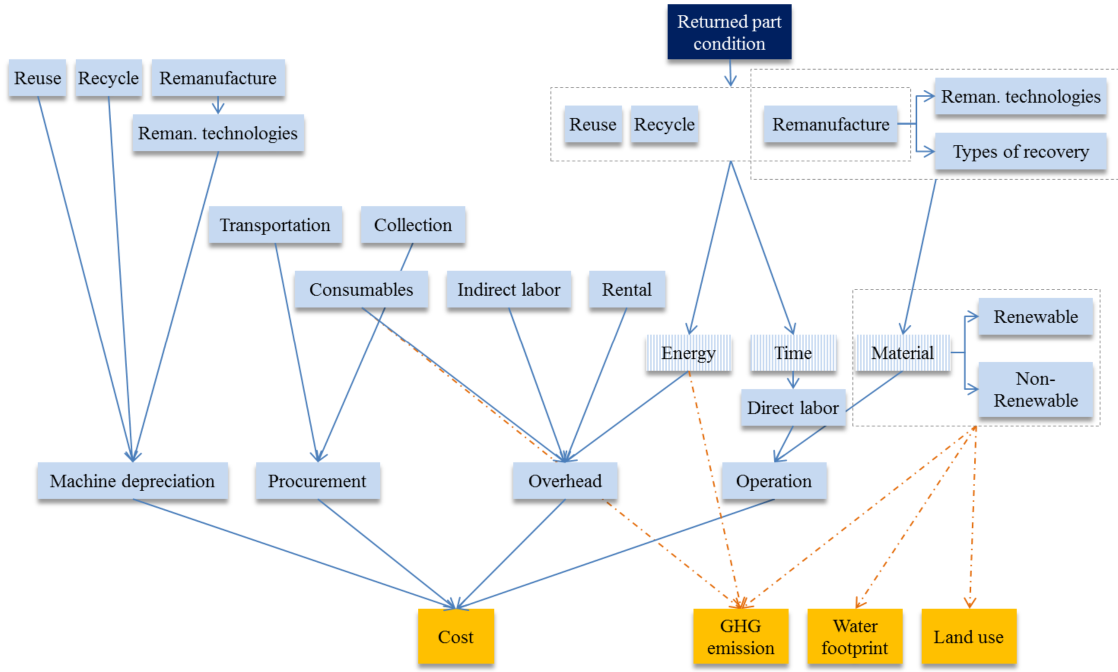


Figure 3-13 Classification of criteria and sub-criteria

3.2.5 Multi-criteria Decision Making Analysis

With the information from ICoBA analysis, decision maker needs to decide the part recovery solution based on the values of identified criteria. However, different measuring unit of criteria gives different perspective for the solution. Moreover, agreement on all criteria cannot be reached to make the final decision in some situations. For example, low profit margin, low carbon emission and least time consumption for reusable part might not be the best solution as compare to a high profit margin with medium carbon emission and medium time consumption for remanufacturable part. It is an important juncture involves in planning and selecting strategies to accomplish company goal. As a result, multi-criteria decision making (MCDM) analysis is required to deal with such trade-off and give an extensive conclusion. A general decision making process (shows in Figure 3-14) is explained.

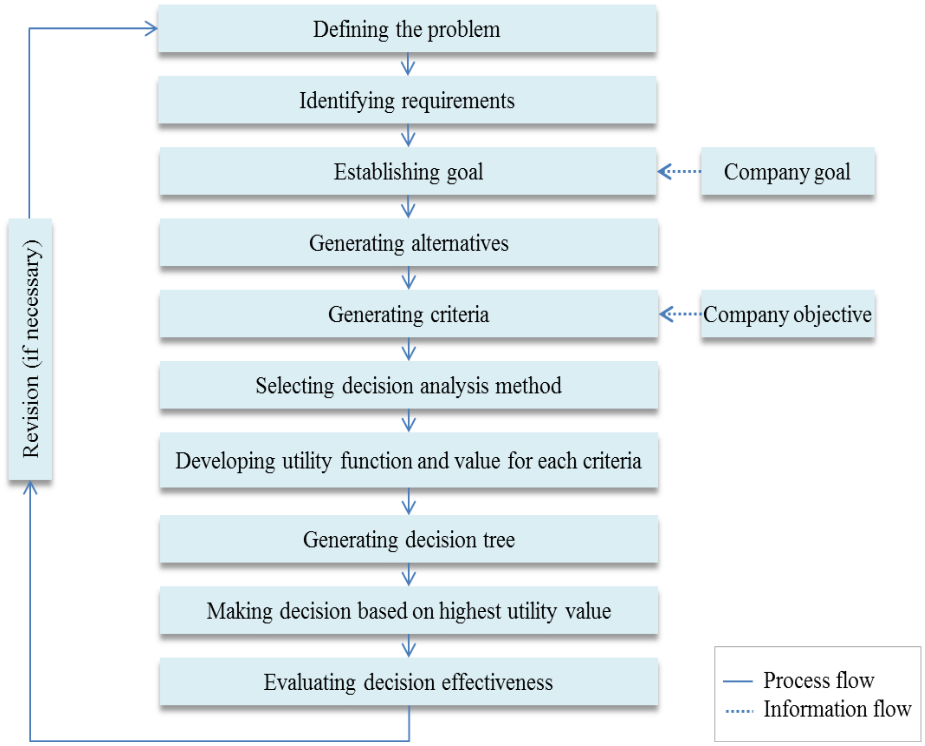


Figure 3-14 Decision making process

<u>Step 1: Defining problem</u>

In view of current nature disasters related to global warming, market competition and employment volatility, consumers could have increased awareness adopting 'green' lifestyle, company are finding ways to gain competitive advantage as well as retain the tacit knowledge that is difficult to transfer from one person to another. A thorough probing on the macro trend of environmental, economy and society would help in revealing clue to the business strategy. This study is carrying out with the premise of the above situations happen. Original equipment manufacturers (OEM) are responsible for product take-back, pressure from shareholder for higher returns, and value creation for customer. Taking the problems into consideration, each subunit within the company is expected to have targets, such as reducing raw material by adding recycled material from EoL product, finding alternatives to manufacture product, developing new approach of logistic planning and so on. Generating these targets becomes the basis for identifying the problem, deciding on the actions taken, and evaluating the outcomes. Overall, understand the problem situation is important as it affects the quality of the decision.

Step 2: Identifying requirements

Requirements are the conditions that must meet in accordance with the problems set. These requirements are the boundary describing the possible solutions to the decision problem. In order to manage the EoL product with returns, manufacturer might need to retrieve the embedded resources from the EoL product efficiently. Thus, manufacturer shall determine the condition at point of return to study the feasibility of part recovery. Information such as part design specification and part reliability data are used as benchmark so that the exact quantitative form of requirement can be stated. The quality of a reusable product shall be as good as new. As for a remanufactured product, same or change of dimension is allowed as long as it meets as new condition. With the exact quantitative form of requirement on hand, it can prevent the ensuing debates on judgmental evaluation.

Step 3: Establishing goal

Goals are the broader statement of desired outcomes toward which effort is directed. In this context, the end goal in decision making is to reach a recovery solution that meet the product technical condition with:

i) lowest possible cost,

ii) lowest possible impact to the environment,

iii) least possible time consumption

Step 4: Generating alternatives

Once the goals have been identified, the next step in the decision making process is to generate alternatives to the goal. Manufacturer has to search for alternative means of reaching the goals. In this step, relevant information and the likely consequences must be gathered. Specifically, manufacturer must seek as much information as possible pertaining to the likelihood of each alternative would result in the achievement of various outcomes. For example, manufacturer should consider the solution of setting up a recycling line or engage the third party recycler could result more cost efficient. Moreover, the extent of generating alternatives is bounded by the importance of decision, cost and value of additional information needed to evaluate the alternative, and number of people affected by the decision [129]. The greater numbers of people involve in the decision, the higher cost of evaluating and lengthy time is required. In this context, the recovery alternatives for EoL part recovery are reuse, remanufacture and recycle.

<u>Step 5: Identifying criteria</u>

With the end goals in mind, criteria among the alternatives can be identified. This step is necessary as the criteria indicate how well each alternative accomplishes the goals. Figure 3-15 shows the structure, where criteria are generated with the information of defined problem and identified alternatives. In this study, decision for the alternative depends on all the criteria.

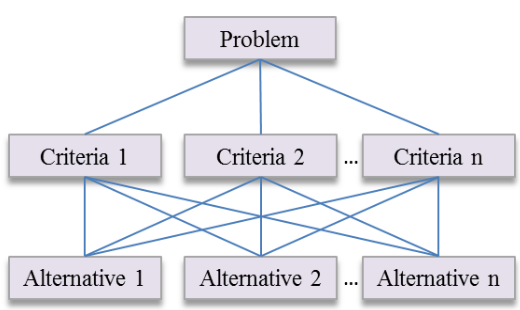


Figure 3-15 Generating criteria and the relationship between criteria and alternative

Step 6: Selecting decision analysis method

There are a number of decision analysis methods for solving the decision problem. Nonetheless, choosing the particular method depends on the complication of the problem, as well as the objective of the decision maker. In some case, it requires integration of few methods to solve a problem. In this study, three sub-goals have been identified, multi-attribute utility theory (MAUT) is applied to handle the tradeoffs among multiple attribute (criteria). This method uses utility functions to convert numerical scales to utility unit scales which allow direct comparison of diverse measures.

Step 7: Define the utility function

The possible consequences of the decision alternatives are captured by three attributes (C_1, C_2 and C_3). Therefore, we need to determine a three-attribute utility function: $u(c_1, c_2, c_3)$. The general rule for MAUT, where $C_1, \ldots, C_n$, n>2, be a set of attributes associated with the consequence of a decision problem. Then, n conditional utilities $u_i(c_i)$ is estimated. The value $u(c_1, \ldots, c_n)$ is computed by combining the $u_i(c_i)$ of all attributes:

$$u(c_1, \ldots, c_n) = f\,[u_1(c_1), \ldots, u_n(c_n)]$$

Step 8: Generating decision tree

When a decision problem concerns multiple alternatives, captured by multiple attributes (criteria), the decision is no longer simple. Decision tree in Figure 3-16 shows the pictorial description of problem that deciding upon part recovery option. The graphical drawing consists of nodes and arcs, where the decision node is presented by square box, chance node is presented by circle and terminal node is presented by triangle. Each alternative is shown as one arc leading away from the decision node towards the right. The values of the eventual outcome are aggregated from the far right towards the decision node on the left. The weightage (w_i or w_{ri}) depends on the decision maker preference or the company policy. Otherwise, a less subjective weightage (w_i or w_{ri}) can be identified using pairwise comparison. The decision tree is solved using TreePlan, an Excel add-in program.

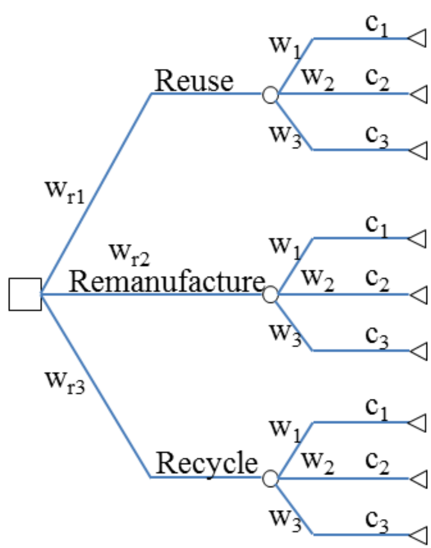


Figure 3-16 Decision tree

<u>Step 9: Making decision based on the highest utility value</u>

A clear defined component is considered in the study to simplify the utility model interacts among attributes. For a consequence set that has attributes of c_1, c_2, ⋯, c_n, its utility is computed using Equation (1).

$$U(c_1, c_2, \cdots, c_n) = w_1 u_1(c_1) + w_2 u_2(c_2) + \cdots + w_n u_n(c_n)$$

$$= \sum_{i=1}^{n} w_i \cdot u_i(c_i) \quad (3\text{-}1)$$

If there is specific preference on certain recovery option over another, the utility value for each alternative is computed using Equation (2). Otherwise, the utility value of the alternative is computed using Equation (3), where

$$u(Alternative\ j) = w_{rj} \cdot \sum_{i=1}^{n} w_i \cdot u_i(c_i) \tag{3-2}$$

$$u(Alternative\ j) = \sum_{i=1}^{n} w_i \cdot u_i(c_i) \tag{3-3}$$

where

w_{rj} is the weight of the j^{th} alternative ($w_{r1} + w_{r2} + \cdots + w_{rj} = 1$)

w_i is the weight of the i^{th} attribute ($w_1 + w_2 + \cdots + w_n = 1$)

$u_i(c_i)$ is the utility function of the i^{th} attribute $0 < u_i(c_i) < 1$

Finally, the decision is made based on the highest utility value.

<u>Step 10: Evaluating effectiveness on decision</u>

The last step in decision making process is evaluating the effectiveness (quality) of the decision. All the process can be done using simulation tool based on user's input, which the simulated results assist in observing the trend. However, in actual case, when an implemented decision does not produce the desired outcomes, revision in part of the process is needed. Typically, inadequate definition of problem is the major flaw. After readdress the problem formulation, user will go through the same process, thus generating new perspective of analysis.

3.2.6 Generate Solution

After getting the final values from previous step, decision maker ought to convert the values into the units relevant to company's target. An example is shown in Figure 3-17, where the target is 20% saving in carbon emission and at least 50% increase in profit within 1 year. If there is *n* parts (of same model) return for the year, each part will be going through the ICoBA analysis and MCDM. The results of all criteria are recorded in the table in Figure 3-15. The values of same component are summed up, and then it is divided by the value of making new part to give the ratio. The lower total amount of carbon emit from recovery will give the higher saving in percentage. The similar principle applies to cost and time component. All these values are then checked with the objectives set in the initial stage. If all the values meet the objective criteria, the final decision can be made. Otherwise, decision maker has to revisit ICoBA analysis to make appropriate adjustment.

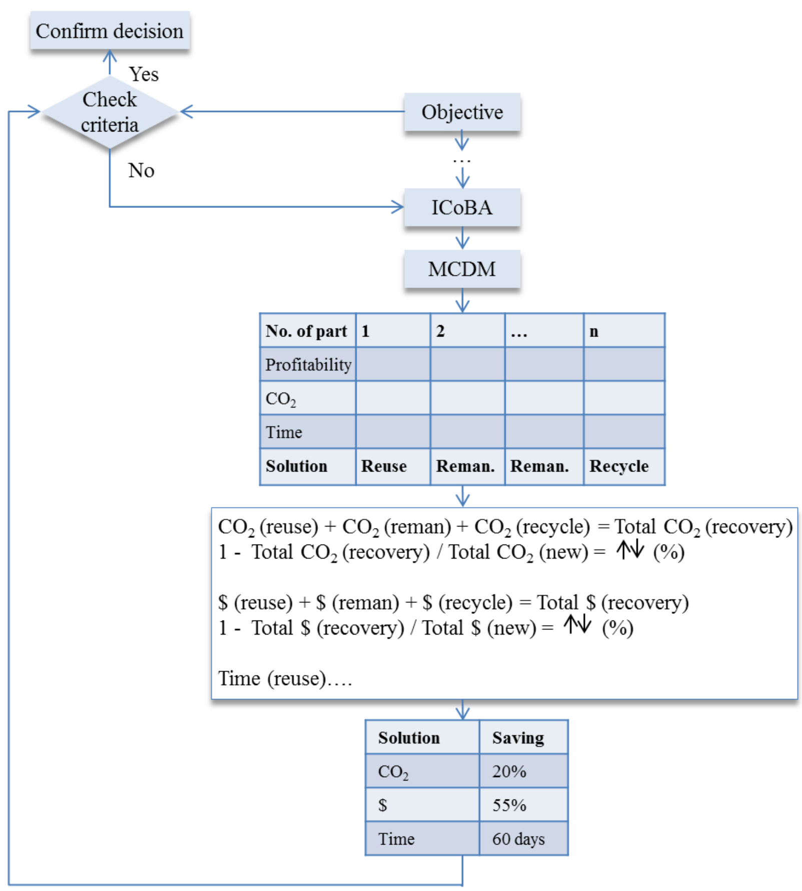


Figure 3-17 Process flow for generating solution and final decision making

3.3 Summary

In this chapter, the overview of product recovery framework is presented, which the framework takes into consideration company goal and target setting. Comprehending the overall framework has set the direction and come out with research framework focuses on EoL product recovery. The research framework includes determination of EoL part condition, characterization using ICoBA analysis and multi-criteria decision making analysis. The chapter ends with solution generation that is useful feedback for company management.

CHAPTER 4

EoL Product Characterization Using Inference Conformity Based Analysis (ICoBA)

This chapter presents the development of models for new and EoL product characterization. As shown in Figure 4-1, the first section of this chapter describes product characteristic and the process flow to generate characteristics for new and EoL product. The characteristics of interest fall into three categories – time, cost and environmental impact. Second section of this chapter explains the assessment flow to determine part condition. The part condition information leads to development of product value models in the subsequent section. This is followed by last section focuses on development of threshold range, which the values set the distinction range for acceptance of characteristic competently. The values are then used as the limit in utility function incorporated with ICoBA which will be illustrated in the case study. The works in this chapter address part of the first and second research question on characterize the EoL product condition and develop models to quantify the condition so that product recovery decision can be made accurately.

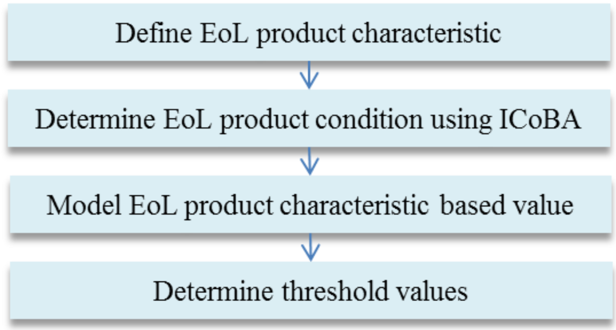


Figure 4-1 Overview of EoL product characterization process

4.1 Definition of EoL Product Characteristics

Product characteristics are the attributes that define a product, such as quality and usability. The features and elements differentiate it among the similar type of product. Three main product characteristics are defined in this study.

- *Time* is referring to process lead time, which the time is required in procurement and manufacture and recover a product. In industry, time reduction is an important action for lean manufacturing. The less time consumes in producing an amount of product, the shorter payback period. However, this characteristic is equally important in product recovery.
- *Cost* is always a consideration in producing any product. It includes the operation cost, material procurement, overhead and machine depreciation along the process chain. This is a critical factor to make final decision whether the product is worth to produce new or reprocess the returned product. Undoubtedly, low cost of manufacturing and recovery is preferred as there is larger room for setting profit margin.

- *Environmental impact* is upcoming key characteristic owing to green consumerism getting more attention. It indicates the environmental consequences resulting from facility's activities, products or service. The examples of major indicators are land and water resource utilization, pollution of water and air resources. In this study, lower environmental impact is favorable as compare to other similar product.

4.1.1 New Product Characteristics

Product characteristic for new product is generated based on the steps show Figure 4-2. The process starts from product design stage, followed by manufacturing. After the product design is finalized in design stage, the product specification is identified and recorded, and then the information is passed to manufacturing department. During product manufacturing, it involves multiple processes. For instance, manufacturing of cast iron mechanical part requires casting, rough and fine processes. Then, the final product will go through several tests to determine product reliability. From the reliability test, engineer would comprehend the overall performance of the component or part, which component or part causes catastrophic impact to the product function. Finally, the product characteristics are generated based on the activities in design and manufacturing stages. The product characteristics are the time and cost consumed along the processes, as well as emission from the processes that have impact to the environment.

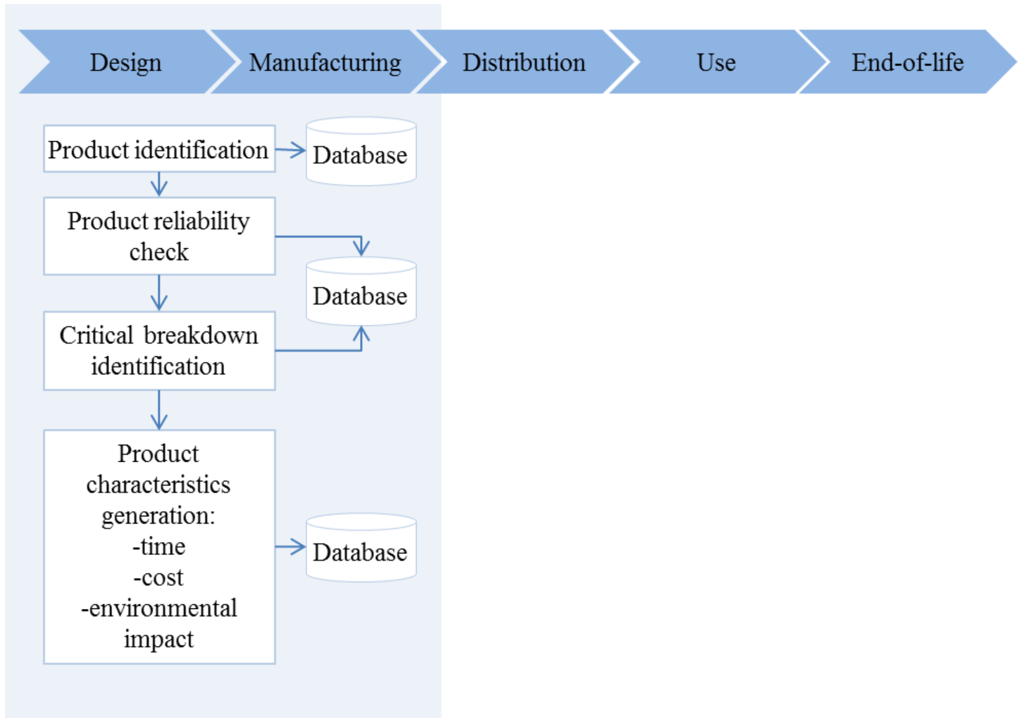


Figure 4-2 Process flow for new product characteristics generation

4.1.2 EoL Product Characteristics

EoL product characteristic refers to the state or quality of the product at the point of return. Generation of EoL product characteristics is shown in Figure 4-3. When the part for recovery is received, the part ought to be verified for the origin manufacturer. With the origin source of part, manufacturer has the access to manufacturing database, therefore the used life and condition of the part can be determined. This is followed by measuring the part to give detail information to judge the part usability.

There are few critical parameters indicating the EoL product characteristic. For the used mechanical parts, characteristics can be determined by the quality and usability. For instance, error tolerance is one of the measures for part quality. While the factors such as wear-out life and cleanliness are related to product usability. In this study, cast iron part in mechanical system involves forces and movement, where part wear and tear

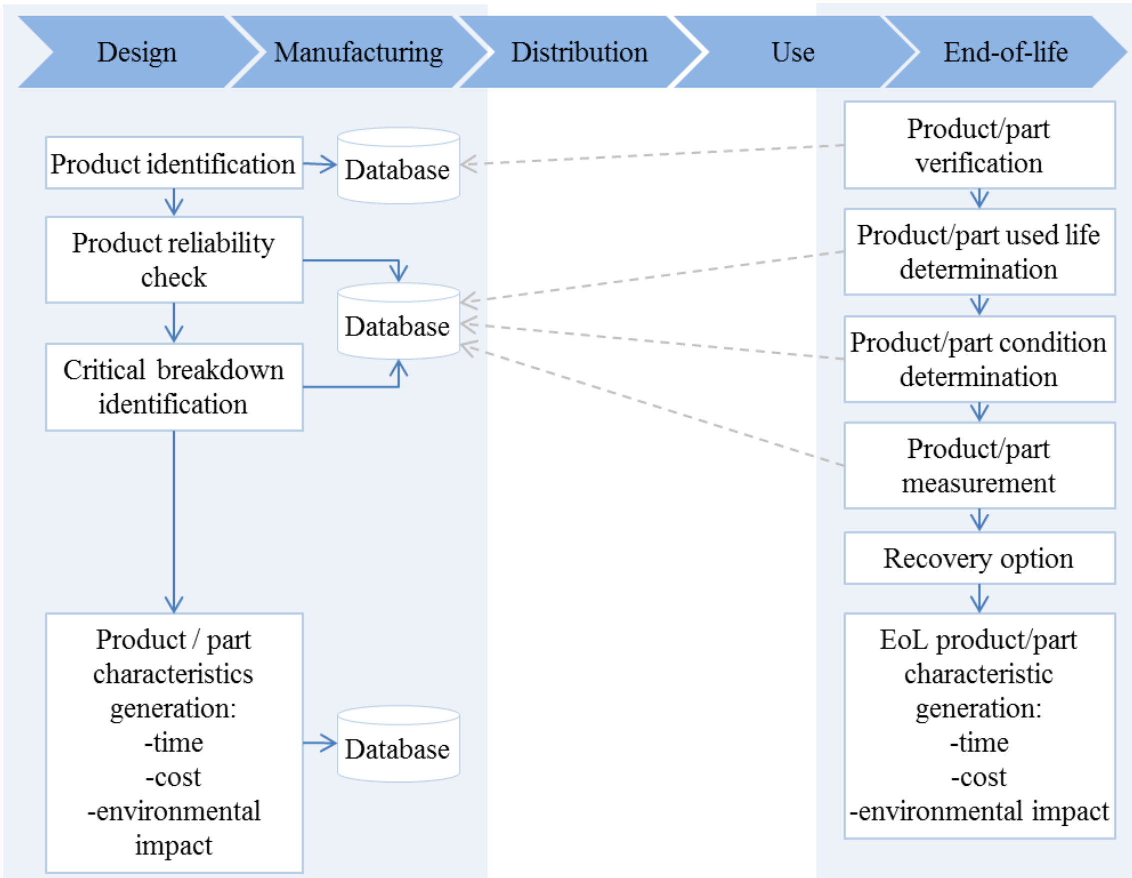


Figure 4-3 Process flow for returned product characteristic generation

is inevitable in this situation. The phenomena of wear and tear might cause product performance stray from the original form and function over time. Thereby, error tolerance in part dimension is determined as one of the critical parameter for part quality. Used life of part is another parameter to verify usability of the returned part. The wear-out life can be estimated by comparing the date of manufactured and date of return. With the information of return channel and life span modeled by manufacturer in reliability test, the part remaining useful life could be predicted more accurately. However, the condition of the part cannot be concluded until measurement is done. Lastly, cleanliness of returned part is definitely an indicator for usability. Cleanliness level presents the part newness, however, it is impossible to reprocess without proper cleaning. The lower level of cleanliness requires more resources to overcome. Classification of the cleanliness level will be given in the following section.

After getting the detailed condition of returned part, part characteristics in terms of time, cost and environmental impact are generated based on recovery options, namely reuse, remanufacture and recycle.

4.2 Determination of EoL Product Condition

This section explains how the condition of returned part is assessed in detail [130], which the process flow is shown in Figure 4-4. Using mechanical part as an example, after the part has been collected, it will be checked for part used life (refer to Section 3.2.2, Figure 3-9). This information is critical in deciding reusability of the part. However, the information is superficial due to unknown usage background. Measuring of part dimension is proposed to further investigate the used life of the part, which the combination of used life and dimension is termed as wear-out life (ie. in terms of cycle, frequency, hours, etc.). If the part is within reusable specification and design life, product characteristic in terms of time, cost and environmental impact for reuse will be estimated. Otherwise, product characteristic based on alternate recovery options are calculated in terms of cost, time and environmental impact. This assessment framework can be also generalized onto other type of product with the critical technical condition such as fatigue strength, corrosion, creep and so on. The following sections introduce the parameters that determine EoL part condition.

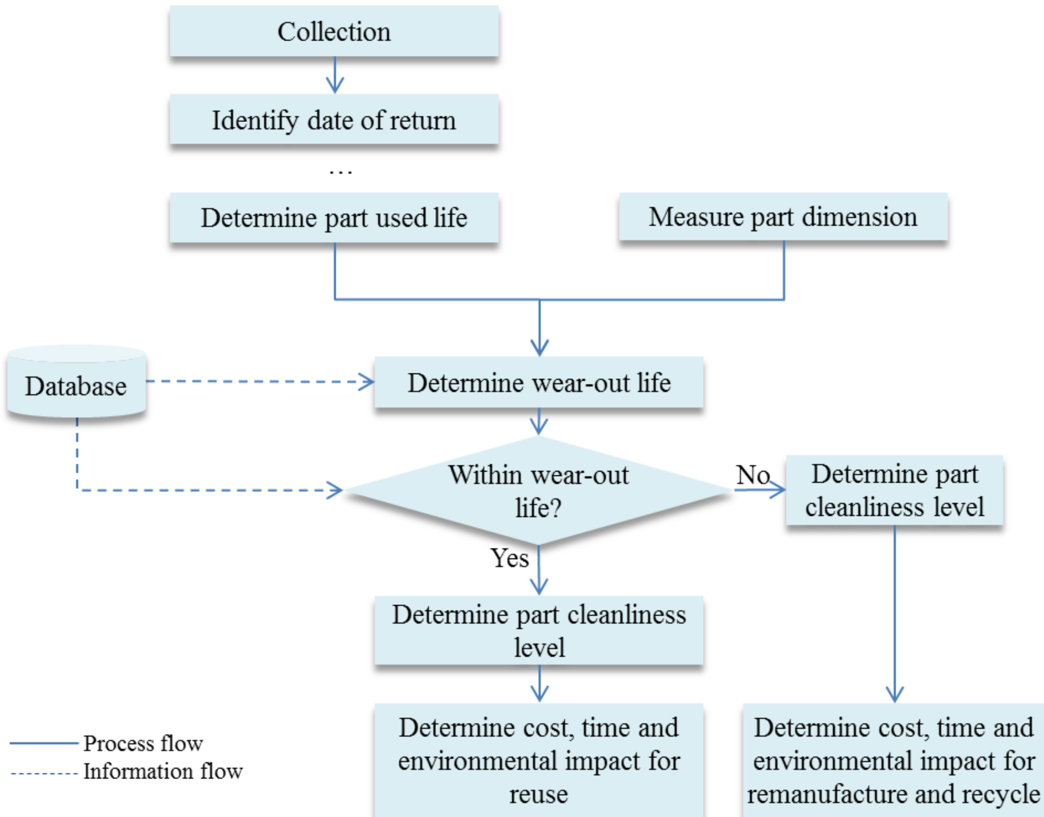


Figure 4-4 Part assessment flow

4.2.1 Wear-out Life

Measurement of wear-out life gives an indication to estimate the remaining life of a product or part after it is collected from user. For most mechanical parts, the remaining life can be measured by comparing the date of manufactured and predicted life span modelled by manufacturer from reliability test.

The bathtub curve in Figure 4-5 is widely used in reliability engineering. It describes a particular form of the hazard function with summation of three characteristics. The first part is decreasing failure rate (formed by red dotted function line), second part is

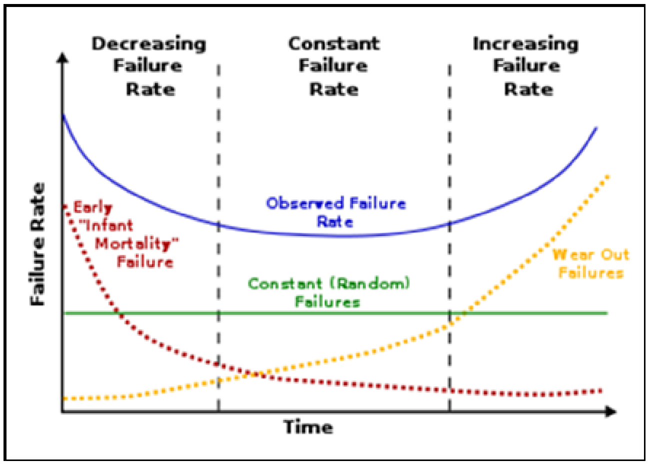


Figure 4-5 Bathtub curve [131]

increasing failure rate (formed by yellow dotted line). The life spans of a product or component usually follow the blue curve described above. This curve can be predicted and modelled by manufacturer during product development phase by collecting and analyzing data through running reliability testing. Manufacturer can also run through the same reliability study process for the subsystem, like part or component. The common methods to determine product reliability are the tests such as accelerated life test, endurance, temperature cycling and so on. This information will help manufacturer to determine the remaining "safe to use" period when the component is collected from known period of usage.

In this study, relationship between technical condition of part and time are proposed to justify the quality at EoL before recovery decision is made. The outcome from wear-out life valuation enables decision maker to make quick decision on whether to reuse the part or product. The yellow dotted line in Figure 4-6 is the wear-out failures function curve. If the wear-out measurement for EoL part is below the designed threshold specification and within designed life, the part is appropriate for reuse. On the other hand, if the used life of EoL part has over the designed life or above the threshold specification, the part is unfit for reuse owing to unwarranted quality of the product beyond design specification. Manufacturer could look into alternative recovery options such as remanufacture and recycle. In order to decide on the recovery option between remanufacture and recycle, manufacturer has to further evaluate the optimal benefit gain from recovering the part based on both options.

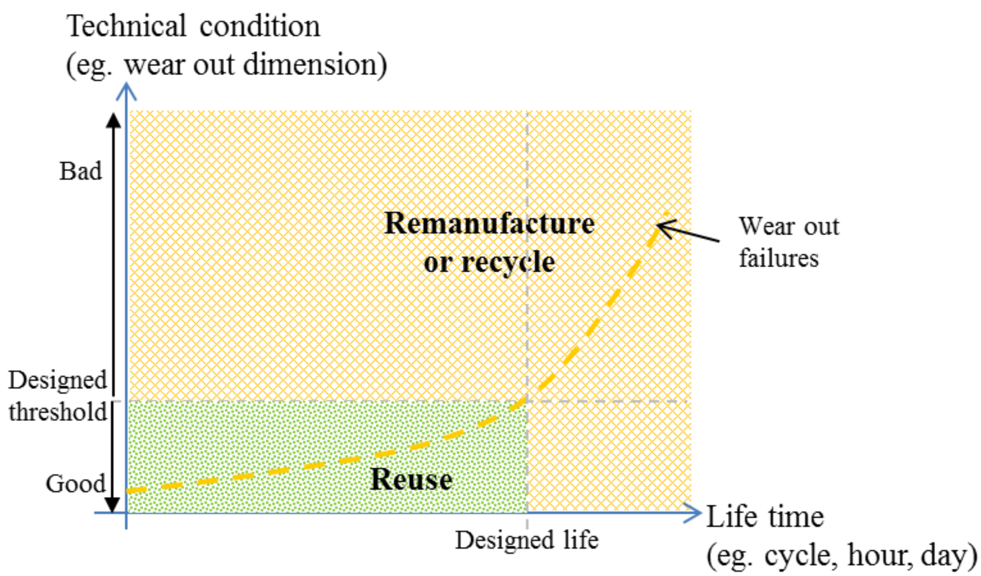


Figure 4-6 Classification of wear-out life for reuse, remanufacture and recycle

4.2.2 Wear-out Dimension

Change of dimension is another common mechanism observed in failure machines or machine parts, where it results in loss of material by mechanical removal. This information not only informs the deformed condition, but also gives a clue on cost computation if the parts are to recover based on different recovery options. The critical problem to solve here involves searching for best method to detect loss of material and how to patch the loss of material.

There are many methods to detect loss of material and many are costly. In any case, the method selected must be the most cost effective and accurate. A simpler method to measure dimension change is using profilometer, where the stylus moves relative to the contact of surface. The measurement method using profilometer could be economical, however, it is time consuming. Another advanced method for thickness measurement called electron energy loss spectroscopy (EELS) is introduced. The theory behind this method is electrons scattering and energy loss. With the information of original dimension, analysis method could be programmed and absolute dimension changed values can be accurately determined in milliseconds. Nevertheless, the equipment could be several times more expensive than profilometer. Taking recovery of high value and large volume product into consideration, return on investment of the advanced machine will be recovered in long term.

The most common methods to patch material on metal part include welding and cladding. Welding is often done by melting the filler material on the part to form join. Many energy sources can be used for welding, like gas flame, electron beam, laser and ultrasound. On the other hand, cladding is a compact technology and has more flexibility on joining different metals.

4.2.3 Cleanliness Level

Cleanliness level of a returned part is another important indicator to quantify the part condition. With a layer of contaminant or dirt covers on the surface, it is impossible to patch the loss material for reuse. Moreover, the dirtier a part is, more steps and cost to clean the part are required. Therefore, inspection of cleanliness level of the part is introduced; however, it depends on the value and type of product sensitivity to cleanliness level. For instance, contaminated or dirty surface of a mechanical part in a compressor might cause bad heat dissipation, lowering flow rate and thus affect the internal pressure and so on. In industry practice, all parts that require cleaning are treated as the worst case. Thereby, the part cleaning line in production is planned in such a way that higher chemical washing concentration or longer washing time is taken so that all dirt will be totally cleaned up.

If cleanliness of a product is particularly important, a manual way of identifying cleanliness level is done via visual inspection, which the labour will sort out the dirty part according to his experience. A more accurate and direct method to recognize the cleanliness of part could be using gravimetric measurement, where a highly sensitive scale can detect gross contaminant. To automate the process, this scale can be integrated with EELS to measure the change of part dimension, at the same time attain the cleanliness status by measuring the gross weight. However, one should ensure the change of part dimension before it goes for gravimetric measurement.

As refer to Table 4-1, the lowest level of cleanliness represents very dirty while the highest level of cleanliness stands for clean. In the initial stage, fine tuning for washing chemical preparation and set up is required to set the amount of one unit of gross contaminant. After the setting, sorting and cleaning process are rather systematic and straight forward. A wiping step is introduced to clean the part with lower level of cleanliness instead of having multiple wash cycle, which this step able to reduce the time and cost of washing greatly. However different wiping time is applied according to the cleanliness level. For example, cleanliness of level 1 requires double the time to wipe the part as compare to the part with cleanliness level 2.

Table 4-1 Classification of cleanliness level

Cleanliness level	Cleanliness measurement and definition	Resource consumption
1: Very dirty	Total weight minus original weight (with 3 or more units of gross contaminant)	2 wiping time plus wash
2: Dirty	Total weight minus original weight (with 2 or more units of gross contaminant)	1 wiping time plus wash
3: Clean	Total weight minus original weight (with 1 unit of gross contaminant)	Wash

4.3 Modeling of EoL Product Characteristic Based Value

This section describes the development of Mathematic models to quantify EoL product value based on the product characteristics identified in earlier steps. The Mathematical models include time, cost and environmental impact [132]. These models aid manufacturer to compute recommended resources in product recovery activities, at the same time visualizes the pro and con among the recovery options. Manufacturing of new part is indicated as $j = 0$, while the recovery options are reuse ($j=1$), remanufacture ($j=2$) and recycle ($j=3$). After this, recovery value of the product based on various recovery options is determined via comparing the resources consumed in manufacturing of new product. EoL product that requires more resources to recover than making a new product has no recovery value.

4.3.1 Time Model

As mentioned in earlier section, time is one of the product characteristics that measures product quality. Equation (4-1) models the time consumed in manufacturing of new part, which consist of processing time (Equation 4-1-a), product function test time (Equation 4-1-b) and reliability test time (Equation 4-1-c). Equation (4-2) describes the time taken in part recovery, while equations (4-2-a) and (4-2-b) are the sub-models in Equation (4-2). As refer to Figure 3-12 in Chapter 3, collection stage involves product disassembly, part cleaning and measurement. The disassembly time spent per part depends on the number of part in a product selected for recovery. The more parts are identified for recovery; less disassembly time is needed per part. Equation (4-2-b) models the re-process stage that includes time component of re-machine, inspection and cleaning. Time required in recycling option shows in Equation (4-3), it composes of time for collection, where the time for collection is made up of disassembly time (in Equation 4-3-a). For the close-loop recycling option, recycled materials are eventually fed as input in manufacturing; thereby time for manufacturing new part is included in Equation (4-3).

$For\ j = 0$

$$\frac{time_j}{unit} = \frac{t_{process}}{unit} + \frac{t_{test}}{unit} + \frac{t_{relia}}{unit} \tag{4-1}$$

$$\frac{t_{process}}{unit} = \sum_{f=1}^{n} \frac{t_{process\_f}}{n_{mfg}} \tag{4-1-a}$$

$$\frac{t_{test}}{unit} = \frac{\frac{\sum_{a=1}^{n} t_{test\_a}}{n_{test\_a}}}{n_{mfg}} \tag{4-1-b}$$

$$\frac{t_{relia}}{unit} = \frac{\frac{\sum_{b=1}^{n} t_{relia\_b}}{n_{relia\_b}}}{n_{mfg}} \tag{4-1-c}$$

$For\ j = 1,\ 2$

$$\frac{time_j}{unit} = \frac{t_{collect}}{unit} + \frac{t_{re-proc}}{unit}, \tag{4-2}$$

$$\frac{t_{collect\_j}}{unit} = \frac{\sum_{c=1}^{n} t_{dis\_c}}{n_{part}} + \frac{\sum_{d=1}^{n} t_{cln1\_d}}{unit} + \frac{\sum_{e=1}^{n} t_{mea\_e}}{unit} , \quad (4\text{-}2\text{-}a)$$

$For\ j = 2$

$$\frac{t_{re-proc}}{unit} = \frac{\sum_{g=1}^{n} t_{rm\_g}}{unit} + \frac{\sum_{h=1}^{n} t_{insp\_h}}{unit} + \frac{\sum_{k=1}^{n} t_{cln2\_k}}{unit} \quad (4\text{-}2\text{-}b)$$

$For\ j = 3$

$$\frac{time_j}{unit} = \frac{t_{collect\_j}}{unit} + \frac{time_0}{unit}, \quad (4\text{-}3)$$

$$\frac{t_{collect\_j}}{unit} = \frac{\sum_{c=1}^{n} t_{dis\_c}}{n_{part}} \quad (4\text{-}3\text{-}a)$$

where

$time_j$ is the total time consumed in manufacturing option j, $j = 0, 1, 2, 3$

$t_{process}$ is the time consumed in manufacturing processes

t_{test} is the time consumed in product function test

t_{relia} is the time consumed in part reliability test

$t_{process\_f}$ is the time consumed in manufacturing process f, $f = 1, 2, 3…$

t_{test_a} is the time consumed in product function testing for step a, $a = 1, 2, 3…$

t_{relia_b} is the time consumed in part reliability testing for step b, $b = 1, 2, 3…$

n_{test_a} is the number of testing unit in step a, $a = 1, 2, 3…$

n_{f_b} is the number of testing unit in step b, $b = 1, 2, 3…$

n_{mfg} is the number of manufactured unit (include defect unit)

n_{part} is the number of part (within a product) chosen for recovery

$t_{collect}$ is the time consumed in collection stage (include disassembly, cleaning, measurement)

$t_{re\text{-}proc}$ is the time consumed in recovery process (include re-machine, inspection, cleaning)

t_{dis_c} is the time consumed in disassembly step *c, c = 1, 2, 3…*

t_{cln1_d} is the time consumed in cleaning step *d, d = 1, 2, 3…* (before recovery process)

t_{cln2_k} is the time consumed in cleaning step *k, k = 1, 2, 3…* (after re-machine)

t_{mea_e} is the time consumed in measuring failure part for step *e, e = 1, 2, 3…*

t_{rm_g} is the time consumed in re-machine step *g, g = 1, 2, 3…*

t_{insp_h} is the time consumed in inspection *h, h = 1, 2, 3…*

4.3.2 Cost Model

Cost is another key concern in any business nature. In this study, cost of manufacturing new product and cost of recovery are evaluated and modeled in Equation (4-4) and Equation (4-5). The unit cost for part manufacturing includes operation cost, overhead cost, procurement cost and cost of machine depreciation. The cost of machine depreciation includes all machine used in particular manufacturing and recovery lines. It is calculated with the assumption of straight line depreciation over 5 years. The operation cost (in Equation 4-4-a) is the total cost of direct material, cost of manufacturing processes and cost of direct labor. Equation (4-4) also applies to calculate EoL product recovery cost, which Equations (4-4-b) and (4-4-c) are the sub-equations. The labor cost is calculated based on the time spent in disassembly, inspection and processes multiply with the hourly rate salary. Cost components listed in Equation (4-4-c) are the direct material and energy cost in re-machine, inspection and cleaning process activities. Cost of manufacturing a new part is included in recycling option (in Equation 4-6) so that all options will end up with a finished part that permits fair comparison. In the models, EoL product condition, change of dimension and the cleanliness level are considered as the function of operational cost. Thereby, looking into product condition gives an insight on the recovery cost.

$For\ j = 0,\ 1,\ 2$

$$\frac{cost_j}{unit} = \frac{c_{op_j}}{unit} + \frac{c_{oh_j}}{unit} + \frac{c_{proc_j}}{unit} + \frac{c_{dep_j}}{n_{mfg\_j(5)}} \tag{4-4}$$

$$\frac{c_{op_j}}{unit} = \left(1 + f_{loss\_j}\right) \times \frac{c_{mat\_j}}{unit} + \sum_{k=1}^{n} \frac{c_{process\_f}}{n_{mfg}} + \frac{c_{labor\_j}}{n_{mfg}} \tag{4-4-a}$$

$For\ j = 1,\ 2$

$$\frac{c_{op_j}}{unit} = \sum_{d=1}^{n} \frac{c_{cln1\_d}}{n_{cln1\_d}} + \frac{c_{labor\_j}}{n_{mfg\_j}} \tag{4-4-b}$$

$For\ j = 2$

$$\frac{c_{op_j}}{unit} = \left[\left(1 + f_{loss\_j}\right) \times \frac{c_{mat\_j}}{unit}\right] + \frac{\sum_{g=1}^{n} c_{rm\_g}}{unit} + \frac{\sum_{h=1}^{n} c_{insp\_h}}{unit} + \sum_{k=1}^{n} \frac{c_{cln2\_k}}{n_{cln2\_k}} \tag{4-4-c}$$

$For\ j = 3$

$$\frac{cost_j}{unit} = \frac{c_{op_j}}{unit} + \frac{c_{oh_j}}{unit} + \frac{c_{proc_j}}{unit} + \frac{c_{dep_j}}{n_{mfg\_j(5)}} + \frac{c_0}{unit} \tag{4-5}$$

$$\frac{c_{op_j}}{unit} = \frac{c_{labor\_j}}{n_{mfg\_j}} \tag{4-5-a}$$

where

c_j is the manufacturing cost for option j, $j = 0, 1, 2, 3$

c_{opj} is the operation cost in manufacturing for option j, $j = 0, 1, 2, 3$

c_{ohj} is the overhead cost in manufacturing for option j, $j = 0, 1, 2, 3$

c_{procj} is the procurement cost in manufacturing for option j, $j = 0, 1, 2, 3$

c_{depj} is the machine depreciation cost in manufacturing for option j, $j = 0, 1, 2, 3$ (assume straight line depreciation over 5 years)

c_{mat_j} is the raw material cost for option j, $j = 0, 1, 2, 3$

$c_{process\_f}$ is the energy cost in manufacturing process for step f, $f = 1, 2, 3\ldots$

c_{labor_j} is the direct labor cost for manufacturing for option j, $j = 0, 1, 2, 3$

c_{cln1_d} is the cleaning cost for step d before re-process, $d = 1, 2, 3\ldots$

c_{rm_g} is the energy cost in re-machine activity for step g, $g = 1, 2, 3\ldots$

c_{insp_h} is the energy cost in inspection activity for step h, $h = 1, 2, 3\ldots$

c_{cln2_k} is the cleaning cost for step k after re-process, $k = 1, 2, 3\ldots$

n_{mfg_j} is the number of manufactured unit for option j, $j = 0, 1, 2, 3$

$n_{mfg\_j(5)}$ is the estimated number of manufactured unit in 5 years

f_{loss_j} is the factor of material loss

4.3.3 Environmental Impact Model

Analysis on environmental impact gives an idea on how green a product is. There is a list of environmental indicators which include physical, biological and chemical measures, such as atmospheric temperature, the concentration of ozone and so on. The measured indicator will be used to communicate the state of environment to the decision maker or general public. Equations (4-6) and (4-7) are the generic models for environmental impact caused in manufacturing new product and EoL product recovery. The environmental impact modeled in all equations are mainly contributed by the electricity consumption in manufacturing and recovery activities, as well as fuel consumption for transportation in procurement. In order to make comparison on the same basis, environmental impact caused in making new product ought to be included in product recycling option, shows in Equation (4-7).

$$For\ j = 0,\ 1,2$$

$$\frac{Environmental\ impact_j}{unit} = \frac{EI_{op\_j}}{unit} + \frac{EI_{proc\_j}}{unit} \tag{4-6}$$

$$For\ j = 3$$

$$\frac{Environmental\ impact_j}{unit} = \frac{EI_{op\_j}}{unit} + \frac{EI_{proc\_j}}{unit} + \frac{Environmental\ impact_0}{unit} \tag{4-7}$$

$$For\ j = 0,\ 1,\ 2,\ 3$$

$$\frac{EI_{op\_j}}{unit} = \sum_{f=1}^{n} \frac{EI_{process\_f}}{n_{mfg\_j}} \tag{4-7-a}$$

where

Environmental impact$_j$ is the environmental impact caused in manufacturing for option j, $j = 0, 1, 2, 3$

EI_{op_j} is the environmental impact caused by operation in manufacturing for option j, $j = 0, 1, 2, 3$

EI_{proc_j} is the environmental impact caused by procurement (transportation) in manufacturing for option j, $j = 0, 1, 2, 3$

$EI_{process\_f}$ is the environmental impact caused in manufacturing process for step f, $f = 1, 2, 3\ldots$

n_{mfg_j} is the number of unit in manufacturing for option j, $j = 0, 1, 2, 3$

4.4 Determination of Threshold Values

In this section, the minimum and maximum values of product characteristic are valuated. Then, these values are set as the range in utility function. The deviation within the threshold gives an indication on the utility in decision making, which will be discussed in the subsequent chapter.

4.4.1 Time Threshold

Figure 4-7 below shows the steps to determine time factor to set the minimum and maximum range for time utility function. The minimum time range is set based on the lowest recovery time option. On the other hand, the maximum time range is set with addition time delay causes along manufacturing and recovery activity. The computation of minimum and maximum time threshold starts with identifying key parameter for time variation in manufacturing and recovery activities. Besides, duration of time delay for each parameter is required to take into account. This is followed by determining the frequency of occurrence within study period (eg. 1 year). After having the delay period and frequency of occurrence, the values are multiplied to obtain the total delay. The total delay is then added up onto the chosen recovery option time to obtain the minimum and maximum time range. In this case, the maximum threshold time is defined as total delay added up with recycling time. This is because the recovery option consumes the longest processing time, which includes the time for manufacturing of new part. On the other hand, reuse option is considered in the minimum threshold time determination.

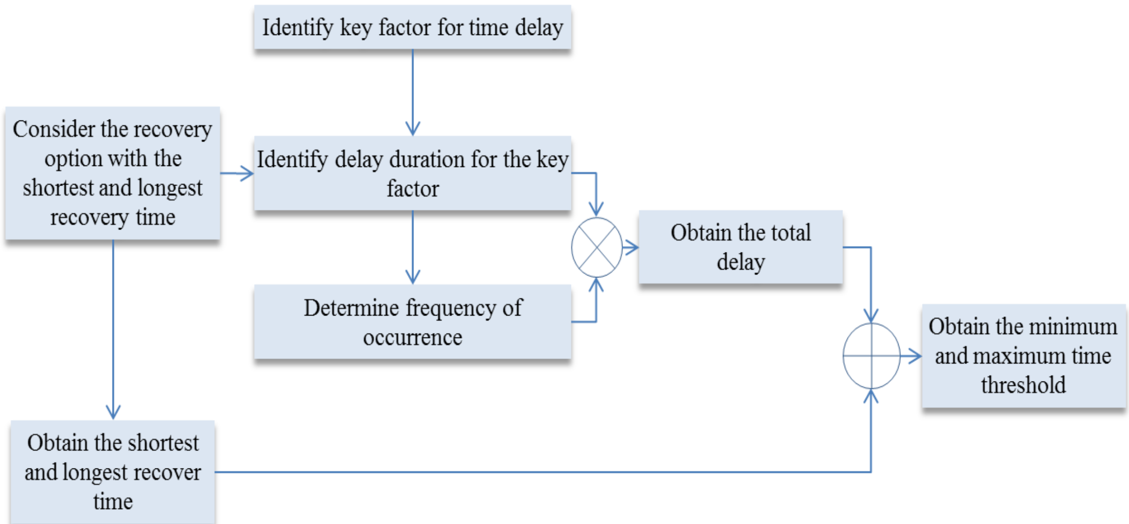


Figure 4-7 Process flow for determination of minimum and maximum time threshold

Six key parameters that are closely related to time delay have been identified in the study (in Table 4-2).

- *Equipment breakdown*: This includes tools and equipment used in the manufacturing and recovery process is malfunction. The equipment could be repaired at the shortest time period if there is local contractor able to response to the request promptly. Otherwise, a longer period is needed to seek expert or even send the equipment back to the origin manufacturer for repair. The drawback impact is big if one of the major machines along the production line is down, thereby subsequence processes will be affected.
- *Short of raw material*: This is common in manufacturing if there is lack of efficient procurement planning. Procurement of material could take up a week or more, this is because of engineer needs to go through the procurement process and

getting approval, plus the delivery time. In most cases, material purchase is provided by the specific supplier. Thus, duration for material purchase is restricted by the availability of material and supplier delivery schedule. This parameter is particularly important for manufacturing of new part. Pending for the raw material, the end product lead time could be prolonged.

- *Short of consumable*: It is as common as short of material if engineer neglects in machine maintenance or consumable stock check. And sometimes, manufacturing or recovery operation has to stop due to short of consumable. However, the waiting time could be half the raw material procurement time. This is because consumable is more general and accessible from suppliers in the local context. Therefore, shorter delivery time is required.
- *Short of manpower*: Manpower refers to the existing engineer or technician absent from work at different station. Production could be interrupted if worker's schedule does not arrange accordingly. Similarly, the following process will be suspended if the staff in particular station absent from work.
- *Power shutdown*: There are two types of power shutdown, which are plant power shutdown and machine power shutdown. If the plant power shutdown happens, meaning all operations have to stop. Likewise, manufacturing or recovery activity would be restrained from production when machine power shutdown. However, power troubleshooting is more straight forward and hence shorter waiting period.
- *Number of recovery part*: Number of recovery part has the biggest impact on disassembly time. The total disassembly time is shared out by the parts within a product chosen for recovery, thus less disassembly time per part it consumed.

Table 4-2 Key parameters for time factor

Key parameters, p_i	**Waiting period (days), d_i**	**Frequency, $freq_i$**
Equipment breakdown, p_1	d_1	Number of breakdown, $freq_1$
Short of raw material, p_2	d_2	Number of shortage, $freq_2$
Short of consumable, p_3	d_3	Number of shortage, $freq_3$
Short of manpower, p_4	d_4	Number of manpower, $freq_4$
Power shutdown, p_5	d_5	Number of shutdown, $freq_5$
Number of recovery part, n_{rec}	NA.	NA.

Finally, the maximum time range can be identified using Equation (4-8), when there is only one part in a product is recovered. All the identified delay parameters are multiplied with the frequency of occurrence and the duration of delay, and then sum the multiplied values with the recovery time. Recycling time ($time_3$) is chosen as the base component because this recovery option consumes the longest time, including time for manufacturing new part. On the other hand, the minimum time range is determined using Equation (4-9), where as many parts as possible are encouraged for recovery. In this case, the minimum time includes time for part reuse, with the minimum number of recovery part of the product is one or more.

$$time_{max} = \left(time_3 + \sum_{i=1}^{n} d_i \times freq_i \middle| n_{rec} = 1 \right) \tag{4-8}$$

$$time_{min} = (time_1 | n_{rec} \geq 1) \tag{4-9}$$

where

$time_{max}$ is the maximum time threshold

$time_{min}$ is the minimum time threshold

$time_3$ is the recovery time for recycle option, $j = 3$

$time_1$ is the recovery time for reuse option, $j = 1$

d_i is the time delay in parameter i, $i = 1, 2, 3\ldots$

$freq_i$ is the frequency of occurrence for parameter i, $i = 1, 2, 3\ldots$

n_{rec} is the number of recover part in a product

4.4.2 Cost Threshold

Figure 4-8 shows the steps to obtain maximum cost range, which will be used in the cost utility function, discuss in next chapter. The process starts with identifying key variables in cost component for manufacturing and recovery activities. These variables are changing with time, for instance, fuel price and electricity unit tariff. After this, unit cost of each variable is identified. This information could be obtained from the updated website or report. This is followed by computing the cost per unit part, then multiply the unit part cost with the incremental factor. As refer to Table 3, the incremental or decremental cost factor for raw material is computed as the difference of material price over the lower material price. The price of material (mtl_h) could be found from the historical data within a period of time (eg. 5 years). Lastly, the total recovery cost is multiplied the factor to obtain the minimum and maximum cost threshold.

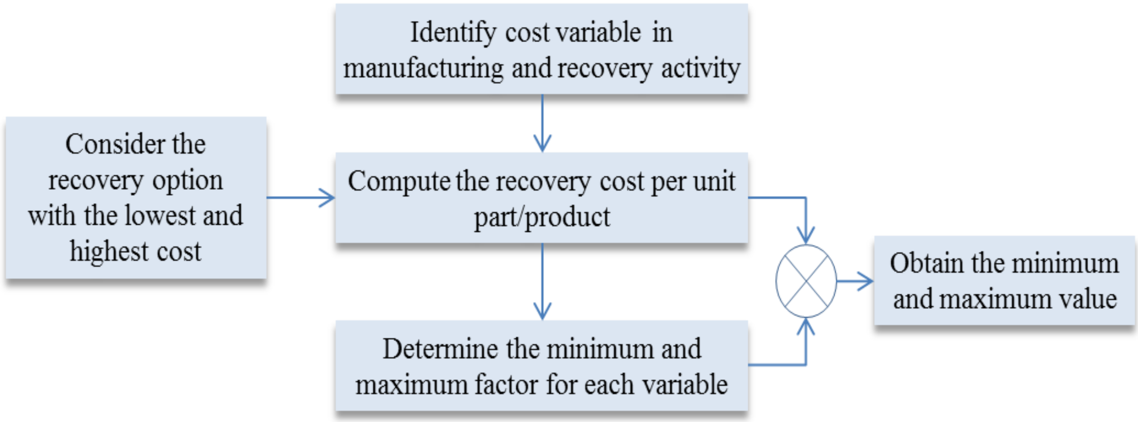


Figure 4-8 Process flow for determination of minimum and maximum cost threshold

The product life cycle cost for mechanical components should include design, procurement, production control, forming, machining, finishing and so on. In this study, four key cost variables have been identified.

- *Cost of raw material:* The cost of raw material is definitely the major cost for a mass produced investment casting item. It could be as high as 80% of the final cost. The unit cost of raw material (u_1) in Table 4-3 and Table 4-4 is varying on day to day basis. Therefore the detail cost must be obtained by contacting suppliers.
- *Cost of electricity:* Cost of electricity is inevitable in any manufacturing house. Electricity is heavily consumed in metal melting and machining activities. On the other hand, light electricity usage happen in assessment and measurement activities. In general, the rise of electricity cost is closely related to the hike of fuel oil price. However, the electricity price change is not as dynamic as cost of material. The detailed database of electricity unit price could be found from the website [133].

- *Cost of fuel*: Fuel is mostly used in transportation in this study. It covers the transportation for raw material, rough product, fine product, end product as well as collection of returned product transfer from one factory to another. Similarly to the cost of material, fuel price fluctuates on daily basis. The current unit fuel cost (u_3) could be found from fuel supplier website [134].
- *Cost of disassembly*: The disassembly cost in this study comprises labor and electricity cost in cutting, dismantling and a series of cleaning steps. From the study, cutting and dismantling cause 50% of the total disassembly cost. The cutting and dismantling cost is incurred for every product goes for recovery. Thereby, as more part in a product is selected for recovery, the lower disassembly cost per part is. Table 4-3 and Table 4-4 also show the maximum and minimum factors, which will be applied in determining the minimum and maximum threshold cost. The maximum factors are applied in the recycling cost component (in Equation 4-5). This is because of recycle option used the greatest cost, including making new part. Thus, multiplying the recycling cost with incremental factor resulted in maximum value for cost in Equation (4-10). On the other hand, minimum factors in Table 4-4 are used in reuse cost component (Equation 4-4). As reuse option spent the least amount and multiply the decremental factor would give the minimum cost threshold using Equation (4-11).

Table 4-3 Key variables and incremental cost factors

Key variable, v_i	**Unit cost, u_i**	**Unit part cost, up_i**	**Factor, f_{max_i}**
Cost of raw material, v_1	u_1	$up_1 = u_1 \times v_{part}$	$f_{\max\_1} = \frac{mtl_h - mtl_l}{mtl_l}$
Cost of electricity, v_2	u_2	$up_2 = u_2 \times \frac{elec_t}{n_{mfg\_j}}$	$f_{\max\_2} = \frac{elec_h - elec_l}{elec_l}$
Cost of fuel, v_3	u_3	$up_3 = u_3 \times \frac{distance}{n_j}$	$f_{\max\_3} = \frac{fuel_h - fuel_l}{fuel_l}$
Cost of disassembly, v_4	u_4	up_4	$f_{\max\_4} = \frac{1}{n_{rec}}, n_{rec} = 1$

Table 4-4 Key variables and decremental cost factors

Key variable, v_i	**Unit cost, u_i**	**Unit part cost, up_i**	**Factor, f_{min_i}**
Cost of raw material, v_1	u_1	$up_1 = u_1 \times v_{part}$	$f_{\min\_1} = \frac{mtl_l - mtl_h}{mtl_l}$
Cost of electricity, v_2	u_2	$up_2 = u_2 \times \frac{elec_t}{n_{mfg\_j}}$	$f_{\min\_2} = \frac{elec_l - elec_h}{elec_l}$
Cost of fuel, v_3	u_3	$up_3 = u_3 \times \frac{distance}{n_j}$	$f_{\min\_3} = \frac{fuel_l - fuel_h}{fuel_l}$
Cost of disassembly, v_4	u_4	up_4	$f_{\min\_4} = \frac{1}{n_{rec}}, n_{rec} \geq 1$

$$cost_{max} = \left(\sum_{i=1}^{n} up_i \times (1 + f_{\max\_i}) \middle| in\ cost_3 \right) \tag{4-10}$$

$$cost_{min} = \left(\sum_{i=1}^{n} up_i \times (1 + f_{\min\_i}) \middle| in\ cost_1 \right) \tag{4-11}$$

where

v_i is the key variable for option i, $i = 1, 2, 3\ldots$

u_i is the current unit cost for option i, $i = 1, 2, 3\ldots$

up_i is the unit part cost for option i, $i = 1, 2, 3\ldots$

f_{max_i} is the incremental factor for option i, $i = 1, 2, 3\ldots$

f_{min_i} is the decremental factor for option i, $i = 1, 2, 3\ldots$

v_{part} is the weight of part in kg

mtl_h is the highest cost of material per kg within study period (eg. 5 years)

mtl_l is the lowest cost of material per kg within study period (eg. 5 years)

$elec_t$ is the total electricity consumption in manufacturing or part recovery

$elec_h$ is the highest cost of electricity per kWh within study period (eg. 5 years)

$elec_l$ is the lowest cost of electricity per kWh within study period (eg. 5 years)

n_{mfg_j} is the number of manufacturing unit for option j, $j = 1, 2, 3\ldots$

distance is the total distance in procurement

n_j is the number of part unit per trip

$fuel_h$ is the highest cost of fuel per liter within study period (eg. 5 years)

$fuel_l$ is the lowest cost of fuel per liter within study period (eg. 5 years)

n_{rec} is the number of recover part within a product

$cost_{max}$ is the maximum cost threshold

$cost_{min}$ is the minimum cost threshold

$cost_3$ is the cost of recycling

$cost_1$ is the cost of reuse

4.4.3 Environmental Impact Threshold

Environmental impact is defined as the actions that significantly affecting the quality of the human environment whether adverse or beneficial, resulting from a facility's activities, products or services [135]. Some examples of environmental impact are air pollution, smog, degradation of aquatic habitat, global warming and conservation of natural resources. On the other hand, environmental aspects are the element of facility, product and service that interact and cause impact to the environment. Therefore, proper study and categorize on the environmental aspects helps people to understand the effect (environmental impact). In addition, measure of the environmental aspects relates the significance of environmental impact. Understanding the consequences, this study proposed a method to improve the impact resulting from manufacturing activity. In the study, environmental impact caused by manufacturing new part (which is the core business) is set as maximum value, using Equation (4-12). In any case, recovery option that falls above the maximum value does not improve the environment. On the contrary, setting the minimum environmental impact value is regard to a country's or company's environmental policy. Taking Singapore as an example, the government announced (in 2007) on reduction of 16% carbon emission by 2020. In order to translate the target to company level, the reduction percentage are used as reference with the assumption of on average every company has to reduce carbon emission by 16% based on business-as-usual (BAU) level. Based on the projected values in 2007 shows in Figure 4-9, there is a need to improve carbon emission by 3.6% annually. Thereby, the minimum environmental impact value is set at 3.6% below the BAU level, shows in Equation (4-13).

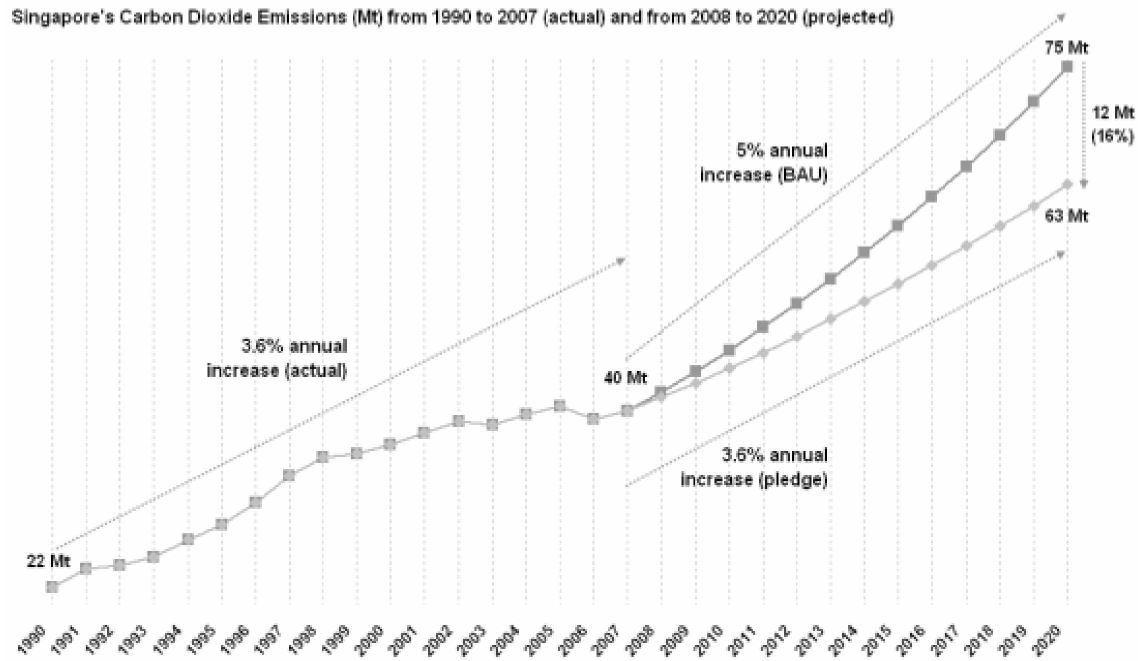


Figure 4-9 Singapore carbon's dioxide emissions (Mt) from 1990 to 2007 (actual) and from 2008 to 2020 (projected) [136]

$$Environmental\ impact_{max} = Environmental\ impact_0 \quad (4\text{-}12)$$

$$Environmental\ impact_{min} = Environmental\ impact_0 - 3.6\% \quad (4\text{-}13)$$

where

$Environmental\ impact_{max}$ is the maximum environmental impact value

$Environmental\ impact_{min}$ is the minimum environmental impact value

$Environmental\ impact_0$ is the environmental impact value of making new part with option $j=0$

4.5 Summary

This chapter presented EoL product characterization using the readily available information in product development and manufacturing phase. The product characteristic based values are cost, time and environmental impact. The values are determined based on the identified parameters - part wear-out life, wear out dimension and cleanliness level. This is followed by development of models for cost, time and environmental impact. Lastly, threshold values are identified and it will be used as the limit in ICoBA.

CHAPTER 5

Decision Analysis for Selection on EoL Product Recovery Options

This chapter explains how the EoL product recovery option is selected via analyzing multi-criteria problem. The solution is generated by going through the decision analysis process shows in Figure 5-1. The procedure for EoL product recovery decision analysis is first introduced, followed by presentation of types of multi-criteria decision making approach. MAUT is selected as the analysis method and the chapter ends with presentation of result using decision tree. The works in this chapter address part of second research question on making consistent decision and third research question on application of the method for decision making.

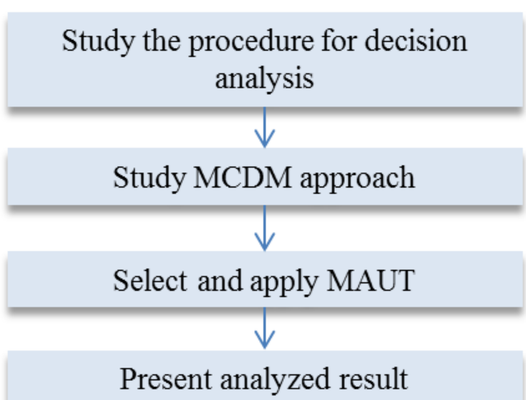


Figure 5-1 Decision analysis process flow

5.1 Procedure for EoL Product Recovery Decision Analysis

Decision analysis is a systematic, quantitative and visual approach to evaluate options encounter in business or even daily life problems. It is based on prescriptive approach, which takes into account normative approach and descriptive approach. Normative approach is concerned with the rationality (eg. optimality), while descriptive approach is concerned with the understanding of humans behavior in making decision. Experiments found that humans do not follow the norms prescribed in normative approach, yet human cognition does not present thoughts in numerical values. As such, prescriptive approach complies fundamentally with normative approach, but it also integrates procedures for decision modeling in regard to human perspective [137].

Manufacturing resource planning and waste management often involves multiple choices with the problem of having multiple criteria. When there is conflict between criteria and the level of conflict is critical, strategic decision technique is needed. It is important to begin the topic with a clear definition of "criteria". According to Oxford Dictionary, "criterion" is defined as "a principle or standard of judging". In decision analysis context, the standard of judging is analyzed for particular option or course of action over the desirable outcome. Considering more than one criterion or course of action is known as *multiple criteria decision analysis (MCDA)*. Next, EoL product recovery decision problem that comes with multiple criteria will go through the following procedure that is categorized in three key phases (shows in Figure 5-2).

- *Phase 1 - Problem identification and structuring*: The starting point of problem identification is coming from the organization, where organization identifies the issue or concern pro-actively on certain aspect for improvement in future.

Otherwise, organization treats the problem re-actively when it recognizes obstacle. Focusing on the manufacturing operation, organization may have expressed interest in exploring certain issue in general, such as one of the following:

- How can existing manufacturing line increase company's profit?
- How can resources be utilized more effectively?
- What can the rejected products contribute to manufacturing line?
- What can be done in order to oblige the environmental regulation?
- How to weigh balance among time, cost benefit and environmental impact?

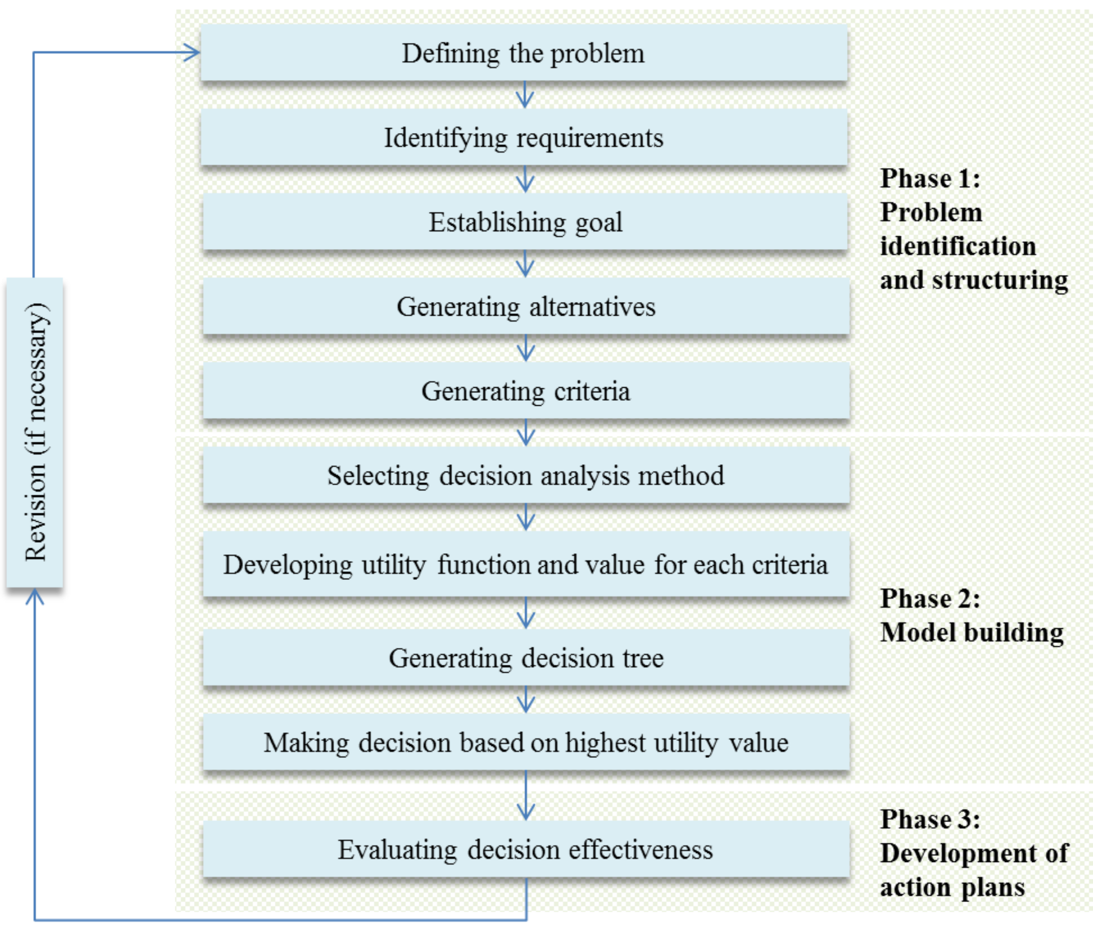


Figure 5-2 Decision making procedure

The problems are viewed in terms of criteria, alternatives, uncertainties, stakeholders, environmental aspects and constraints. After the problems are clearly understood and identified, idea that relevance to the problem is generated. Often, the ideas are overwhelming and idea grouping is needed to better structure the problem for further analysis. A simple illustration of problem structuring using cognitive map is shown in Figure 5-3. In this study, three alternatives have been identified, which are reuse, remanufacture and recycle. These alternatives is considering for best tradeoff among the three attributes: time, cost and environmental impact.

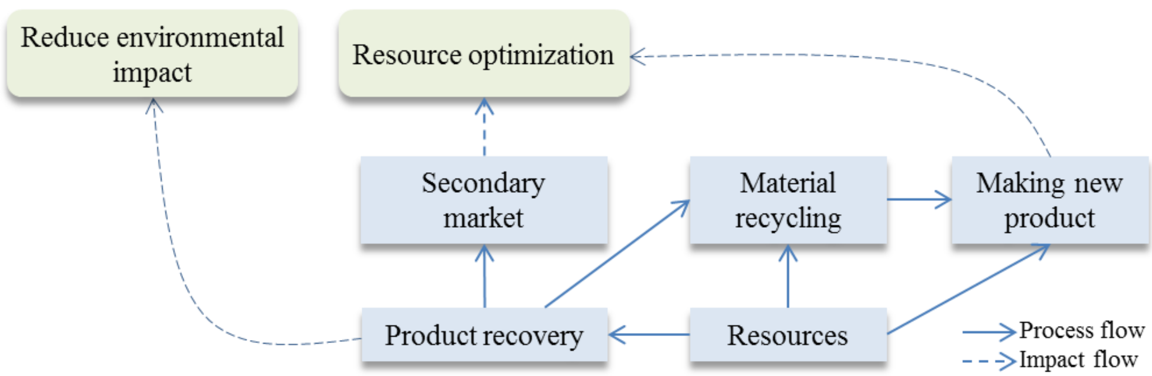


Figure 5-3 Portion of cognitive map for idea generation

- *Phase 2 - Model building*: The main purpose of MCDA is to develop models based on decision maker's preferences, constraints, goals, etc. Therefore, outcome of the alternatives or action under consideration gives consistent guidance to the decision maker in search of the preferred solution. It is necessary to construct some form of models that represent decision maker's preference and value judgment, which consist of two components – preference for each criterion and aggregation model. The former component sets the relative importance or desirability for achieving certain level of performance. And the latter component allows inter-criteria comparison and combination of preferences across criteria.

Referring the tree diagram in Figure 5-4, the aggregation would need to be repeated from the higher hierarchy level (far right) to the next lower level until it reaches overall aggregation (far left). For example, aggregation of criteria starts from "Technology / process", "Direct labor" and "Material" in terms of "Operation". Thereafter, aggregation of "Procurement", "Overhead", "Operation" and "Machine depreciation" would generate corresponding preference in terms of "Economic benefits". This process will continue until the overall preference is achieved by aggregating "Time benefit", "Economic benefit" and "Environmental benefit" for a particular option. The same processes are also repeated for all the recovery options.

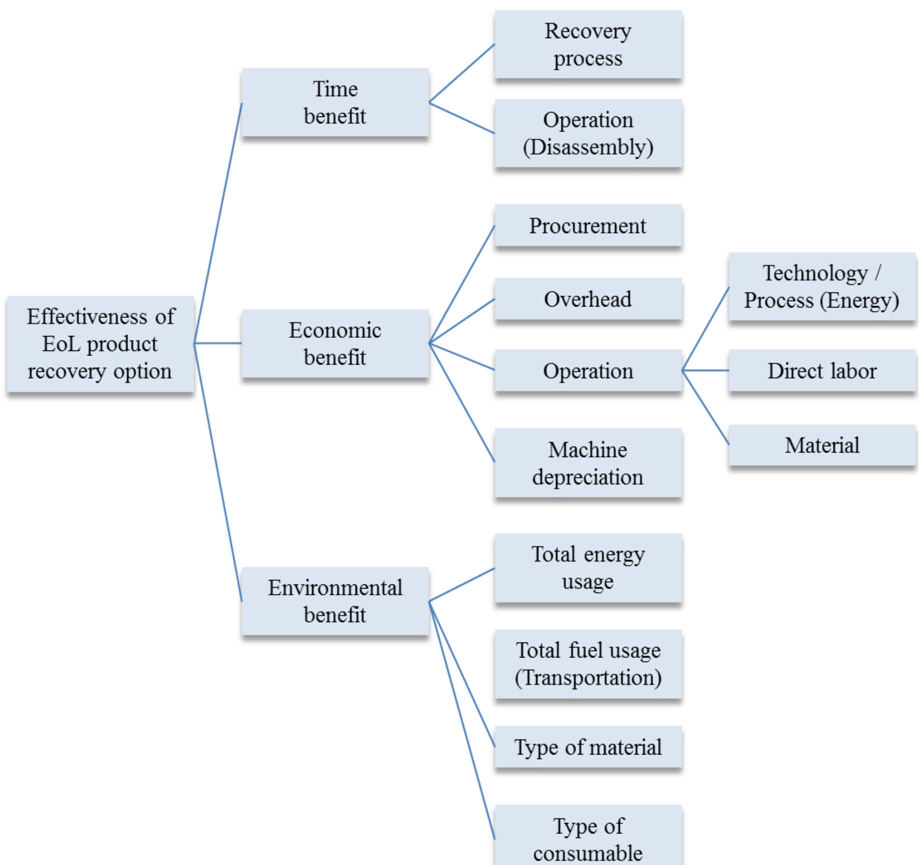


Figure 5-4 Decision model building

- *Phase 3 - Development of action plans*: Outcome of the analysis does not solve the problem until the result is translated into specific action plan. The decision making process not only performs technical modeling, but it also gives insight to the implementation. Sometimes, making decision is not straight forward as we perceived when it involves higher level of complexity such as influences from political point of view or multiple participant decision making. Therefore, revision of problem definition and structure, sorting, ranking and alternative is necessary to suit the particular situation.

5.2 Overview of Multi Criteria Decision Making (MCDM) Approach

As mentioned in Chapter 2, MCDM is a general term to describe a collection of approaches that handle decisions matter. The methods of MCDM are broadly categorized into multi-attribute decision making (MADM) and multi-objective decision making (MODM). MADM methods contain value measurement theory, where the methods handle the problem with limited number of predetermined alternatives. MODM methods function as satisficing a goal, which the decision variable has infinite or a large number of choices. Other methods that work on outranking are AHP, TOPSIS, PROMETHEE and so on. The classification of MCDM approaches are illustrated in Figure 5-5.

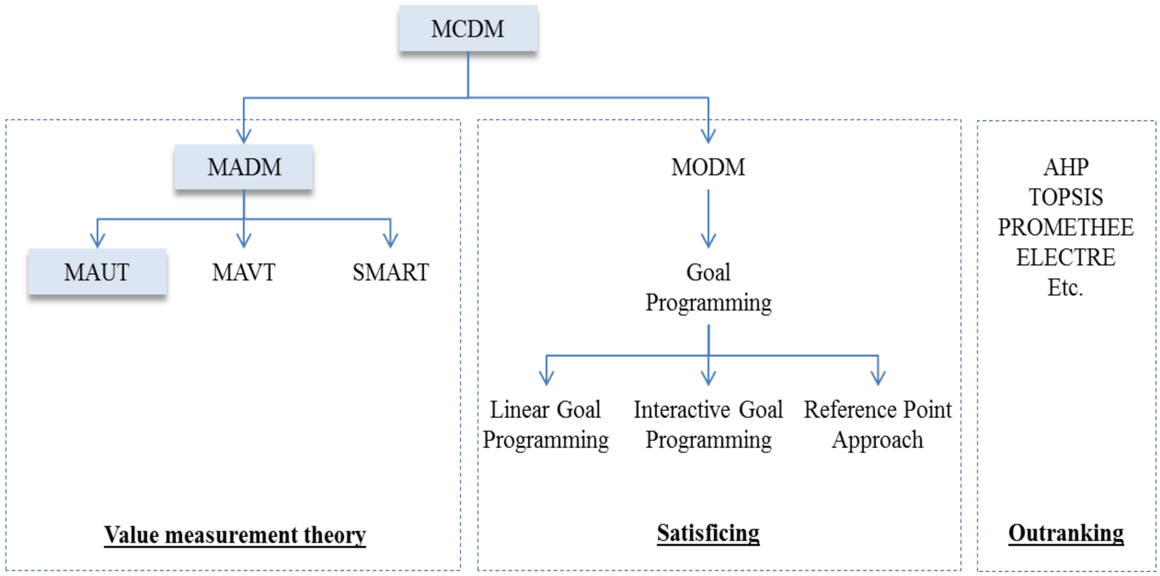


Figure 5-5 MCDM approaches

Understanding the decision problem in earlier stage helps to identify a set of definite alternatives. Moreover, with the available product information and data, it opens up knowledge in recognizing MCDM approaches. The MCDM approaches are value measurement theory, satisficing and outranking.

- *Value measurement theory*: The preference model in this approach is constructed associates with real number in each alternative. Thereby, the derived preference on alternatives is consistent with decision maker’s judgment value. However, the prerequisite for the value function must constitute complete weak/strength order, and the preferences or indifferences are transitive.
- *Satisficing*: Preference model in this approach focuses on achieving satisfactory level on each criterion. After one criterion is satisfied, the consideration is shifted to achieve other criterion. This method is particularly useful for screening of alternatives.

- *Outranking*: Outranking preference model is generated by some form of weighted pairwise voting procedure, by taking into account all available information regarding the problem. The output of analysis is ranking relation in the set of alternative rather than numerical value. This method could facilitate in giving the dominant trend for the problem with ordinal or cardinal scale of criteria, however imprecise measures.

Considering both the characteristics of definite number of alternatives and value based preference model, MADM is the appropriate approach to implement in this study. In view of MADM approach, there are multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT) and simple multi-attribute rating technique (SMART). MAUT or MAVT is one of the more commonly applied multi-criteria methods. Both of the methods work about the similar principle, except MAUT coping with uncertainty and risk. On the other hand, SMART uses direct rating and ratio weighting procedures for constructing utility function.

5.3 Application of Multi-attribute Utility Theory (MAUT)

With the consideration of risk in EoL product recovery decision making, MAUT is chosen to analyze the decision problem. This section describes the general idea on application of MAUT and determination of utility function. MAUT was developed by R.L. Keeney, and the detail knowledge can be found in the literatures [138-140]. Knowing the set of alternatives, criteria and constraints, MAUT is appropriate to study the details and relationships between criteria. This is because MAUT is a structured method to handle the tradeoffs among multiple attributes. Moreover, it is a systematic approach to quantify decision maker's preference.

Application of MAUT process (in Figure 5-6) starts with defining the utility function, $u_i(c_i)$, which the method uses 0-1 scale to measure level of preference. Scale of 0 refers to least favorable and scale of 1 refers to most favorable. This is followed by defining and standardizing the partial value function. Typically, the "worst" (least favorable) and "best" (most favorable) resulted values need to be described for each criterion using particular value functions. These values could be on different scale and unit, shows in Figure 5-7. Then, the values are standardized to 0 at the "worst" and 1 at the "best" outcome. Determination of the "worst" (eg. $time_{max}$, $cost_{max}$, environmental $impact_{max}$) and "best" (eg. $time_{min}$, $cost_{min}$, environmental $impact_{min}$) values have been explained in Chapter 4. However, in real case, decision maker might have preference over one criterion to another. In order to enable the preference consideration, weight for each criterion is identified and used as scaling factor. In other words, the degree of importance is embedded using the method. Finally, the overall score (using Equation 5-1) for alternative j, $u(j)$ is obtained by aggregating the scores from multiple criteria, where each criterion is formed by multiplication of weights, w_i with the utility function, $u_i(c_i)$. Additive aggregation is applied in this study for simply explanation and easily understood by people with different background. Through MAUT technique, it is possible to scale the diverse measures into uniform measure and thus direct comparison can be made. On top of that, the numerical end result is used to rank the alternative options.

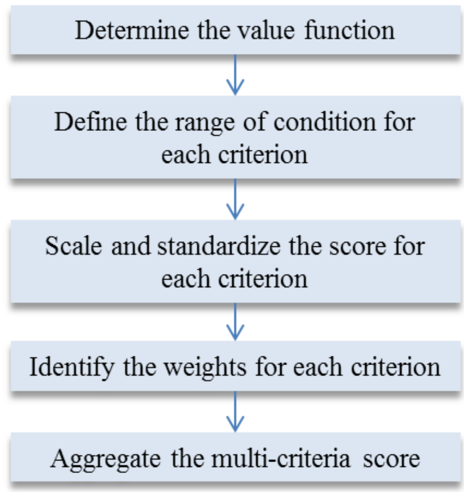


Figure 5-6 Procedure for determination of MAUT for decision model

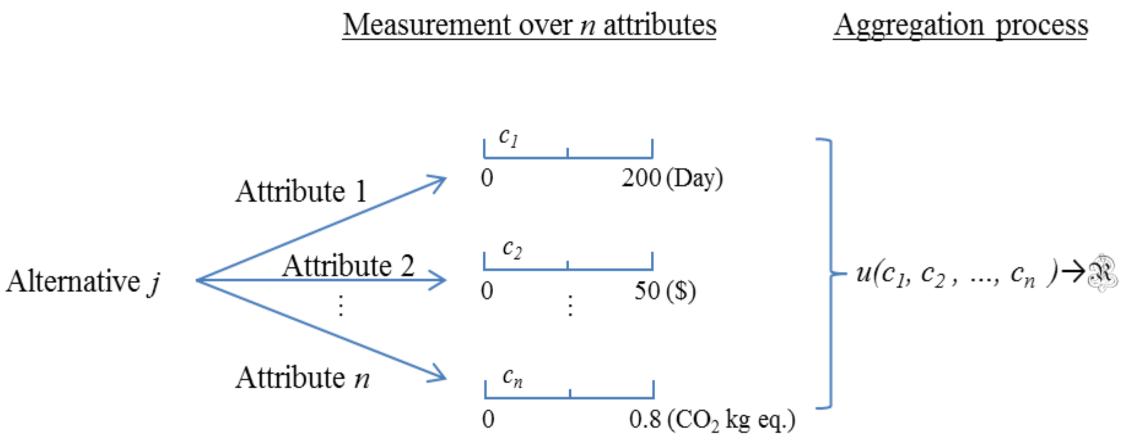


Figure 5-7 Measurement of n attributes with different scale and unit

$$u(j) = \sum_{i=1}^{n} w_i \cdot u_i(c_i) \tag{5-1}$$

where

w_i is the weight of the i^{th} attribute ($w_1 + w_2 + \cdots + w_n = 1$)

$u_i(c_i)$ is the utility function of the i^{th} attribute $0 < u_i(c_i) < 1$

5.3.1 Determination of Utility Function

Looking into the details of first step as mentioned above, this section describes the steps to determine utility function, shows in Figure 5-8. Utility is a way to describe preferences, and a utility function assigns a number to every possible consumption bundle, such as more preferred choice get assigned the larger number than less preferred choice. This property is important as it categorizes the bundle of goods. Determination of multi-attribute utility function is done using the following steps as explained in R.L. Keeney's work [139].

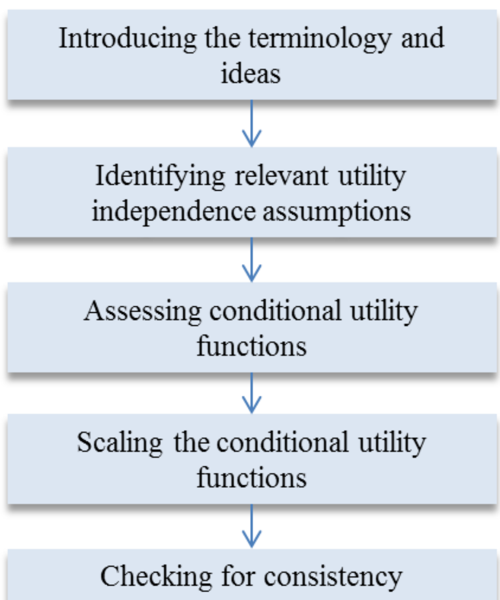


Figure 5-8 Procedure for assessing multi-attribute utility functions

Firstly, the terminology and ideas for the solution have to be well-defined so that people from different background could easily grasp the concept. In this study, attributes, c_i are the characteristics identified in Chapter 3, which are time (c_1), cost (c_2) and environmental impact (c_3). Alternatives j are reuse (j = 1), remanufacture (j = 2) and recycle (j = 3). The hierarchy model of the decision problem is shown in Figure 5-9 and the decision is made based on the highest aggregation score.

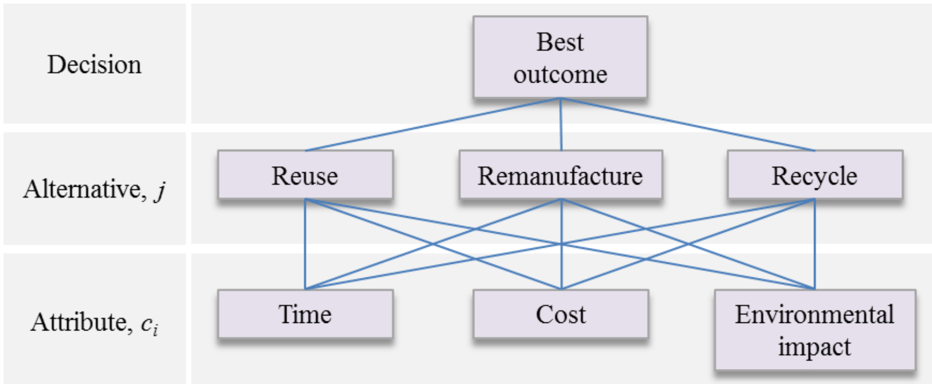


Figure 5-9 Hierarchy model for decision problem

Secondly, the analyst needs to verify utility independence of the attributes. Three key conditions and assumptions must hold before the utility function is valid. They are *preference independence*, *utility independence* and *additive independence*. If the conditions are fulfilled, it would greatly simplify the assessment of utility function. In this study, the sub-criteria in time, cost and environmental impact are grouped accordingly. For instance, change of using greener material might affect the processing time (t_{proc}) of making product. This is followed by change of total cost due to higher material cost (c_{mtr}) and labor cost (c_{labor}) based on varying processing time and cost of energy (c_{energy}) to process the material. Production of the product using green material reduces the environmental impact (EI_{proc}). However, the specific reduction value [139] in EI_{proc} does not affect the preference of attributes time and cost. Therefore, time (c_1) and cost (c_2) are preferentially independence of environmental impact (c_3).

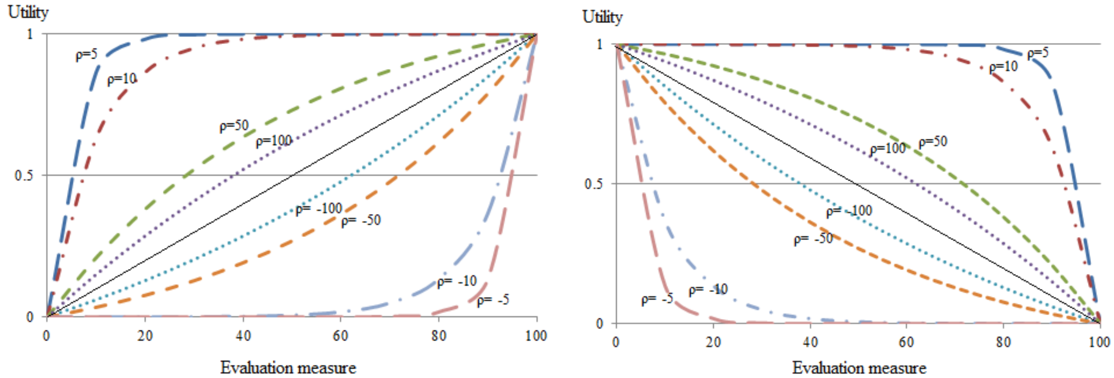
Table 5-1 Grouping of sub-criteria

Criteria	Time	Cost	Environmental Impact
Material	t_{proc_mtr}	c_{mtr}	EI_{proc_mtr}
Process	t_{proc}	c_{labor} c_{energy}	EI_{proc}

Thirdly, the conditional utility function of each attribute is assessed subjected to the unit and scale of measurement (refer to Figure 5-7).

Fourthly, the measured results are scaled against 0 to 1 to have a common utility level. There are infinite ways to describe preferences, such as linear function, quadratic function and exponential function. In this study, exponential shape is taken into consideration. This function had been reviewed and often provides adequate approximation for the utility function [141]. Taking risk tolerance (ρ) of the decision maker into consideration, risk adverse attitude always has a utility function with the concave shape. On the other hand, risk seeking attitude always has a convex utility function shape. A risk neutral decision maker has a straight line utility function, shows Figure 5-10. The increasing preferences curves in Figure 5-10 (a) are used to measure the outcome in terms of gain. The curves are plotted using function in Equation (5-2), that is larger amount of x is preferred to smaller amount. On the contrary, the decreasing preferences curves in Figure 5-10 (b) are measuring loss such as time and cost. They are plotted using function in Equation (5-3).

Lastly, the consistency of utility function is verified by further checking the preference with decision maker.



(a) Increasing preference (b) Decreasing preference

Figure 5-10 Exponential value functions

$$u(x) = \begin{cases} \dfrac{1-e^{-(x-Low)/\rho}}{1-e^{-(High-Low)/\rho}}, & \rho \neq \text{Infinity} \\ \dfrac{x-Low}{High-Low}, & otherwise \end{cases} \qquad (5\text{-}2)$$

$$u(x) = \begin{cases} \dfrac{1-e^{-(High-x)/\rho}}{1-e^{-(High-Low)/\rho}}, & \rho \neq \text{Infinity} \\ \dfrac{High-x}{High-Low}, & otherwise \end{cases} \qquad (5\text{-}3)$$

5.3.2 Types of Aggregation Method

When the decision problem involves two or more attributes, modeling of preferences is no longer simple. Building a utility function that implies interactions among the attributes is getting more complicated. Knowing the characteristic of utility functions and importance of each criteria, the prime interest here is aggregating a number of different criteria (say $u_i(c_i)$ for $i = 1, 2, \ldots, m$) into an multi-attribute utility function (say U(**c**), where **c** = $c_1, c_2, \ldots c_m$). Additive approach is the basic modeling in MAUT. With the variants and a number of interaction coefficients, multiplicative and multilinear utility functions are derived. These functions consider aggregated utility, attribute weights, utility levels and interaction coefficients.

For the subsequent analysis in MAUT, additive aggregation is implemented. It is a simplified utility model that ignores interactions among attributes. One of the reasons for using additive aggregation is that it is the most easily understand form by various backgrounds of people. Reading from literatures in fact concludes that many applications in practice tend to use additive model rather than multilinear or multiplicative models. Also, a number of simulations reported that using of additive model for realistic range of settings introduce extremely small error as compare to multiplicative or multilinear model (such as over-linearization) [140, 141]. As such, the use of additive utility function for decision making is likely to be more than adequate in the wide variety of settings.

As explained above, the simplicity of additive aggregation is somehow attractive. However, some additional assumptions are required so that additive aggregation becomes valid.

i) *Preferential independence*: This assumption has indicated in the previous section, however, the section further explains the additive assumption for the case of three attributes. Considering the three attributes (eg. time, cost and environmental impact) associated with the measurable alternatives (eg. reuse, remanufacture and recycle) represented by the point (1, 2 and 3) in three dimensional planes. The illustration gives an intuitive sight of relationships among preferentially independence conditions.

(a) Coordinate {X,Y} is preferentially independence of Z,

(b) Coordinate {Y, Z} is preferentially independence of X, and

(c) Coordinate {X, Z} is preferentially independence of Y

If we refer to Figure 5-11 point 3, change of C' to C" in y-plane and change of T' to T" in x-plane do not affect the result in z-plane. Similarly, change of C' to C" in y-plane and change of E' to E" in z-plane do not affect the result in x-plane. This principle can be repeated for point 1 and 2. Now it can be reasonably concluded that the decision problem is preferential independence.

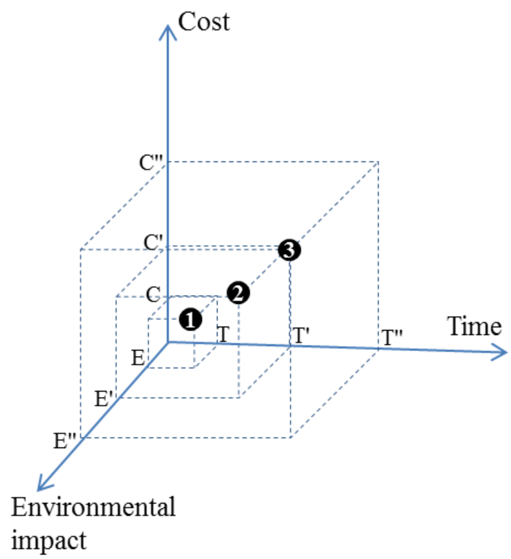


Figure 5-11 Three-dimensional preferential independence

ii) *Interval scale property*: This assumption refers to addition or subtraction of a constant term to each attribute measure will not affect the preference ordering by the resultant value. The addition simply redefines the performance level from its origin level. As illustrate in Figure 5-12, addition of constant k to the cost does not change the preference ordering.

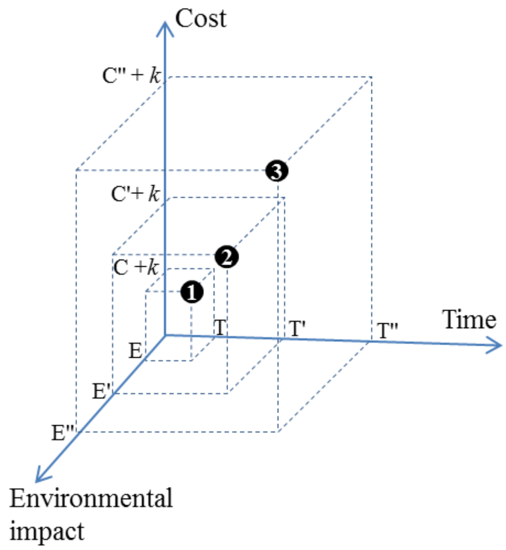


Figure 5-12 Interval scale independence

iii) *Weights as scaling constant*: Numerical weight parameter (w_i) has a very significant algebraic meaning, as people are often refer to the relative importance of the criteria on numerical scale. The relative importance of attributes c_i, which is represented by weights are finite positive real numbers. However, these numbers may not necessary be the same meaning as the numerical value in the additive value function. The weights here are simply the scaling constant that constructs different level of scale measurement. There are many techniques to determine attribute weights, methods that elicit the weights by focusing on comparisons between two attributes at a time, such as AHP [142], SMART [56], SWING [143] and tradeoff weighting. The decision maker is asked to provide relative important (weight) of one attribute and compare to the other attribute. Bias could arise due to use of different range of attributes as well as restriction on the weighting scale. However, there is no superior weighting method. For particular application, the weighting methods can be combined and weighting procedures can be adapted.

Suppose that the utility functions for the three attributes have been generated, satisfying the preferential independence and interval scale properties. Assessment of the weights then validates the additive utility function, in Equation (5-1).

5.3.3 Weights Assessment using Analytic Hierarchy Process (AHP)

Experience and literature evidence suggest that people conveniently express the strength of their preference or opinion using verbal expressions. For instance, one criterion is ‘strongly more important’ than the other. In this case, AHP method able to translate the intuitive statement into numerical scale. Using the example just mentioned, the nine point integer scale describes the verbal expression as ‘five times as important as’ another. Moreover, one level of value tree (in Figure 5-13) is classified in this decision problem has eliminated the errors caused in structure of value tree. The weight for recovery option *j* is accumulated from the weight generated in each attribute *i*, $w_i(j)$, which the formula shows in Equation (5-4).

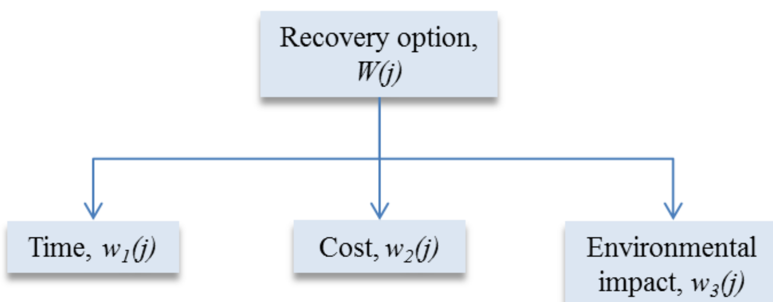


Figure 5-13 Value tree for decision making

$$W(j) = \sum_{i=1}^{n} w_i(j) = 1 \qquad (5\text{-}4)$$

Decision maker should be aware of AHP is appropriate for this decision model but not equally apply to all decision models. This is because the meaning of weights varies between models, also lack of background information render to erroneous outcome. The AHP can be implemented using the five consecutive steps, shows in Figure 5-14.

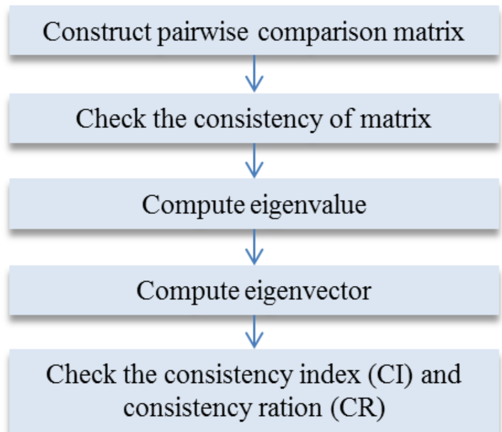


Figure 5-14 Procedure for assessing weights using AHP

Step 1: Construct pairwise comparison matrix

Suppose we have n attribute or criteria to compare. Therefore, we first create a table consists of all criteria for pairwise comparison. Table 5-2 shows an example of pairwise comparison table, seeking for the weights of three attributes require in the decision problem. Each criterion in the column is required to compare for the relative importance to the criteria in the row, one at a time. The intensity of importance scale is shown in Appendix A1. After the data entry, matrix A is formed as shows in Equation (5-5), with each element $a_{ij} = w_i/w_j$ for all i, j. However, decision maker needs to satisfy the following rules to validate the matrix.

(i) The entries of A must be positive, ie. $a_{ij} > 0$ for all i, j

(ii) The matrix A is a reciprocal matrix with $a_{ij} = 1/a_{ji}$ for all i, j

(iii) The diagonal element of A are always 1

Table 5-2 Pairwise comparison between attributes

	Time, c_1	**Cost, c_2**	**Environmental impact, c_3**
Time, c_1	1	1/5	1/3
Cost, c_2	5	1	3
Environmental impact, c_3	3	1/3	1

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = [a_{ij}] \tag{5-5}$$

Using the example, the weight of c_2 is about five times that of c_1, the weight of c_2 is about thrice that of c_3 and the weight of c_3 is about thrice that of c_1.

$$\frac{w_2}{w_1} \approx 5; \frac{w_2}{w_3} \approx 3; \frac{w_3}{w_1} \approx 3$$

Then $a_{21} = 5$, $a_{23} = 3$ and $a_{31} = 3$.

The pairwise matrix for c_1, c_2 and c_3 is as follow:

$$A = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{3} \\ 5 & 1 & 3 \\ 3 & \frac{1}{3} & 1 \end{bmatrix}$$

Step 2: Check the consistency of matrix

A perfectly consistent pairwise comparison matrix is a valid A-matrix, shows in Equation (5-6). Therefore, it simplifies the identification of relation A and eigenvector w, using Equation (5-7).

$$a_{ij} = \frac{a_{ik}}{a_{jk}} = a_{ik}a_{kj} \tag{5-6}$$

$$(\boldsymbol{A} - n\mathbf{I})\ w = 0 \tag{5-7}$$

w can be direct assessed using Equation (5-8).

$$w_i = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad \forall i = 1,2,\ldots n \tag{5-8}$$

However in reality, A is usually imperfect as the entries are based on human judgment. Hence, the best estimate for w can be estimated from the relation $(A - n\lambda)w = 0$, where λ is eigenvalue (a constant that is approximately equal to n).

Step 3: Compute eigenvalue, λ

Consider the matrix A is imperfect, taking the determinant of the coefficient matrix as zero, illustrates in Equation. λ can be determined by solving the matrix. The solution has only one real dominant eigenvalue, which is denoted as λ_{max}.

$$Det(A - \lambda I)\begin{vmatrix} 1-\lambda & \frac{1}{5} & \frac{1}{3} \\ 5 & 1-\lambda & 3 \\ 3 & \frac{1}{3} & 1-\lambda \end{vmatrix} = 0 \tag{5-9}$$

Step 4: Compute eigenvector, w

After solving the matrix, λ is inserted in the following equations to solve w_1, w_2, and w_3.

$$\lambda w_1 + \frac{1}{5}w_2 + \frac{1}{3}w_3 = 0$$

$$w_1 - \lambda w_2 + w_3 = 0$$

$$w_1 + \frac{1}{3}w_2 + \lambda w_3 = 0$$

$$w_1 + w_2 + w_3 = 1$$

Step 5: Check the consistency index and ratio

In practice, entries of pairwise values cannot guarantee matrix *A* is perfect. Errors and inconsistency in judgment cannot be totally avoided. In order to ensure matrix *A* remain consistencies, Consistency Index (CI) is computed using Equation (5-10). Inconsistency increases with the increase amount of ($\lambda_{max} - n$). The identified CI can then check with the average CI values called Random Indices (RI) given in Appendix A2.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5-10}$$

Besides, the Consistency Ratio (CR) is checked using Equation (5-11). A matrix that satisfies CR ≤ 0.1 is considered acceptable.

$$\mathrm{CR} = \frac{\mathrm{CI\ of\ A}}{\mathrm{RI\ for\ size}\ n} \tag{5-11}$$

5.4 Presentation of Result using Decision Tree

In the last step before decision is made, all the available information is presented using the classical Decision Tree in Figure 5-15. There are two types of nodes in the decision trees:

- *Decision nodes* are presented by squares. These are points on the tree where the decision maker makes the choice based on the highest utility value.
- *Chance nodes* are presented by circles. These are points on the tree where the decision maker does not have control over the outcome.

There are three possible outcomes, *j* which the outcome is determined by accumulating result from attribute, c_i whose utility values, $u_i(c_i)$ are assessed separately. In this study, the resultant value of attribute, c_{ij} is dependent on alternative *j*. Thereby, utility for particular attribute c_{ij} is denoted as $u_i(c_{ij})$. Utility value for all j is calculated using Equation (5-12). The highest utility value is chosen as the final decision.

$$u(j) = \sum_{j=1}^{n} \sum_{i=1}^{n} w_i \cdot u_i(c_{ij}) \tag{5-12}$$

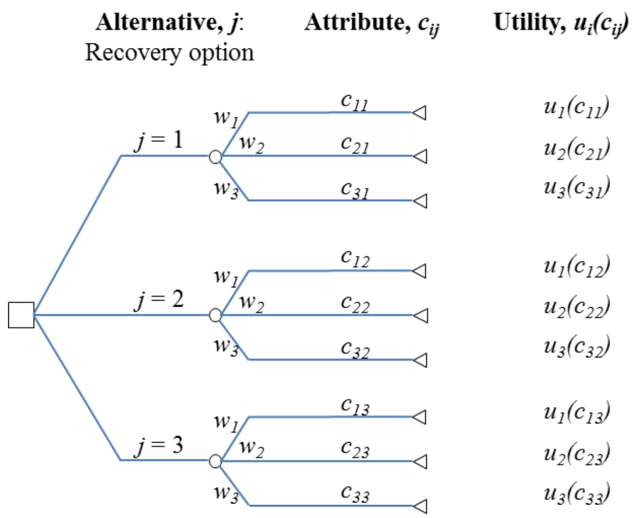


Figure 5-15 Decision tree

5.5 Summary

This chapter explained the purpose and application of decision analysis for EoL product recovery. The procedure for decision analysis applies on EoL product recovery is presented in detail. Moreover, various types of MCDA approaches are categorized and introduced. With the clear understanding on MCDA approaches, MAUT is identified as the decision analysis method to solve EoL product recovery decision problem. Lastly, the steps for application of MAUT on EoL product recovery are described in detail.

CHAPTER 6

Case Study

In order to evaluate and validate the proposed research framework and developed models, this chapter presents the case studies using ICoBA analysis method to support EoL product recovery decision making. The decision making is illustrated using an industrial case with two scenarios. A reciprocating compressor is selected as the case study, looking into the best recovery decision for production reject in the first scenario and end-of-use return in the second scenario, as summarized in Table 6-1. Valuation on different scenarios is to test and prove the validity of the developed method used in real and different environment under different constraints. In addition, it is prime important to check the validity of model and gather feedback information to improve evaluation process in this phase. Data for the case study on compressor of household refrigerator are collected from the industrial partner Company Z, one of the leading compressor manufacturers worldwide. Lab data have also been used as supplementary information in recovery activities. In the case of unavailable and confidential data, a comprehensive literature search is done on publicly available data to enrich the case study.

Refrigerator compressor is a complex product. It consists of approximately hundred parts, covering majority of cast iron part, copper wire, magnet, few plastics, and paper. Assembly of compressor is done in a way that lower lever sub-parts are subsequently mounted onto the upper level sub-parts until it reaches the uppermost level.

Table 6-1 Features of case study

Features	Scenario 1	Scenario 2
Type of product	Compressor of household refrigerator	
Product structure	Multiple part product	
Type of part	Block	Crankshaft
Type of usage	Continuous (24 hours)	
Return channel	Production reject	End-of-use

Compressor is constructed with electromotive element and compressing element. The compressing element is rotated and driven by electromotive element, as shows in Figure 6-1. Electromotive element includes stator and rotor, position at the upper portion of compressor. Compressing element is disposed below the electromotive element, comprises crankshaft, block and piston.

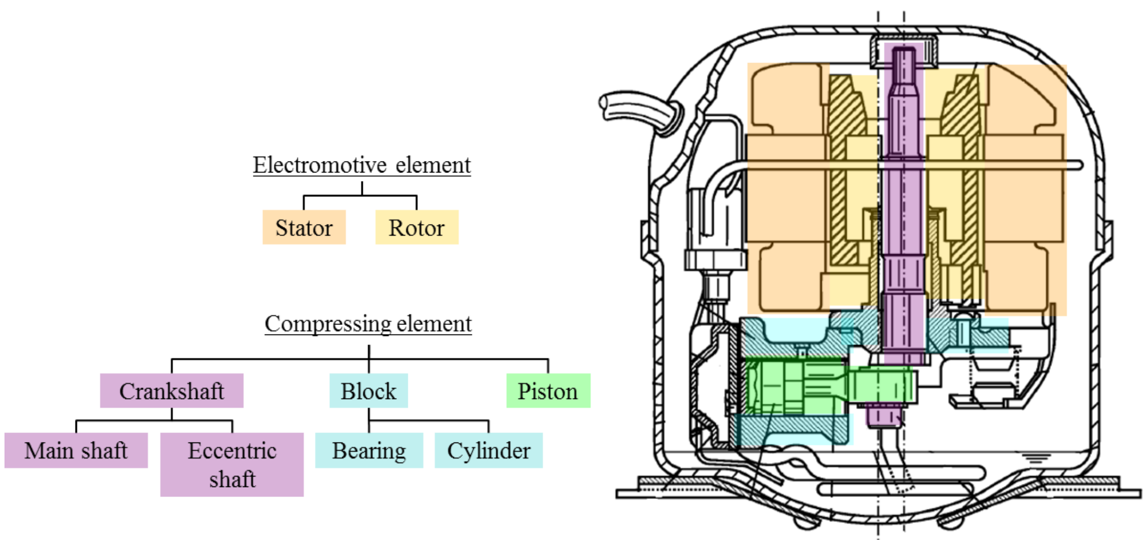


Figure 6-1 Compressor structure of household refrigerator

Crankshaft and block are selected as the part for recovery. Firstly, this is because they are one of the valuable parts in the compressor. Secondly, the parts are made of significantly more weight of material than others. And thirdly, assessment for mechanical part is more general and straight forward as compare to electronic part. Recovery of block will be illustrated in the first scenario, and recover of crankshaft will be presented in the second scenario.

Undoubtedly, compressor of household refrigerator operates under daily condition. Thereby, the continuous compression operation causes some of the parts have more intensive wear and tear than others. Reliability data is collected during product development stage, where the critical part wear and tear is tested under different period of cycle, various temperature and pressure settings.

On top of the myriad product features covered in this chapter, the validation approach for each scenario will give an insight on different perspectives. For instance, the reusability threshold for each scenario is carefully determined to recognize the quality of part for reusability potential. Assumptions have been made particularly when usage data are not available.

Finally, validation of the research method is performed using two scenarios. The method is implemented on part or product in production reject and end-of-use returned product. The details of the validation approach used in each scenario will be outlined in the subsequent section.

6.1 EoL Parts Recovery in Refrigerator Compressor

6.1.1 Case Study Description

The case study focuses on evaluation of EoL compressor to support decision making in salvaging the parts in compressor. Salvage of used good parts possible to retrieve most of the embedded resources in making a new one. However, new resources are committed in order to retrieve the existing valuable resources. The balance resources gain from consuming and retrieving is straight forward if the resources involve only one aspect (eg. cost). However, decision making involves many considerations from different aspects. In this study, it covers cost aspect as it is the most common measure in business practice. Time is another dimension that measures the dynamic of the action. Thirdly, with the existing and upcoming environmental regulations, environmental impact is included in the case studies to preempt the regulations. With the advancement of technology and knowledge, manufacturers today are endowed with reusing and remanufacturing capabilities, thus eco-friendly treatment of EoL product is no longer confined to recycling or proper disposal methods.

6.1.2 Methodology

The methodology described herein offers a system to which OEMs can quantify the value of the returned products. The part recovery follows the product recovery framework in Chapter 3, followed by the assessment flow to identify the condition of EoL part. After the basics are established, scenario in the relevant section will elaborate the stepped process of determining the value of used products. The thesis constructs a system to compute the innate value of used products, which will be fed into the later steps of the recovery framework. Essentially, companies are required to perform a one-time mining of relevant information for their products, apply them to the models proposed, in order to optimize the choice of recovery option It is recommended here that manufacturers rely on the *a posteriori* face value of returned products; in other words, the product's value is determined at the point of return, rather than predicted from usage patterns since the point of sales. To balance the trade-off between cost effectiveness and comprehensiveness, data analyzed has to be easily producible, yet collectively exhaustive. Against this backdrop, the framework can be applied to empower OEMs to systematically analyze the extent of their product's sustainability. With a number of recovery possibilities, the suggested solution enters the fray and assists in the electing the optimal option.

6.1.3 Basic Premise

Life Cycle Assessment (LCA) is utilized as the premise for developing the model. The study assumes OEMs conduct product take-back, so the LCA is bounded by material extraction to manufacturing to the EoL stage, which incorporates recovery of returned product in a closed-loop fashion.

The consideration of recovery options (reusing, remanufacturing and recycling) thus offer alternative treatment of returned products, as shown in Figure 6-2. For these options, the system assumes that reusing does not be repaired the product to pristine condition, that is, take it in as-is quality; remanufacturing restores the product to good-as-new condition and recycling as self-explanatory, and they eventually restart the life cycle to end up with a new product.

The EoL compressors are collected when new compressors are delivered to refrigerator production house. Therefore, resources spent in collection stage are omitted in the study.

6.1.4 Description of Options

It is important to appreciate the manner in which the thesis purports the types of used product recovery options. Figure 6-2 is a generic representation of the LCA processes for various reprocessing scenarios (red). But first, the LCA processes for a new part (blue) are explained as they are fundamental to forming two of the reprocessing options

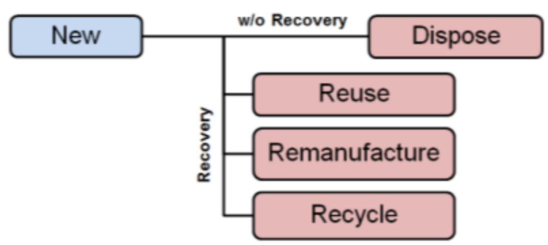


Figure 6-2 Default and recovery paths

- **New part:** As per the depiction in Table 6-2, a new part first exists from material extraction, undergoes casting, rough process, followed by fine machining. It is then cleaned and inspected, before being assembled and distributed. Collection from end user is included in the LCA diagram of a new part by virtue of the assumption that the OEM exercises product take-back.
- **Recovery part**: In each of the three recovery options (Table 6-2), the processes of storage, disassembly and sorting are common. Regardless of the recovery option

executed, the product at EoL will again return to the OEM due to take-back. With this understanding, the three reprocessing options are described below:

(i) Reuse: The first recovery alternative is reuse. In this recovery option, the tested part is inspected and channeled to assembly and distribution. No repair of filling is done on the part.

(ii) Remanufacture: In remanufacturing, the tested part is cladded before undergoing fine machining, cleaning and inspection. Remanufacturing in the form of cladding (for metals) restores the part to good-as-new condition. After these, the part is finally assembled and distributed.

(iii) Recycle: In recycling, the part is sorted out and transported to the foundry for recycling, which basically involves melting the metal components. The recycled metal is indirectly channeled back to production as the part begins a partially new lease of life and follows the production of a new part. A proportion of virgin material will be mixed with the recycled metal in order to maintain the material quality.

Table 6-2 LCA steps for new and recovery part

Product life cycle stage	Process step			
Material extraction	▪ Material production	-	-	▪ Material production
Manufacturing	▪ Casting ▪ Rough process ▪ Fine process ▪ Cleaning	-	-	▪ Casting ▪ Rough process ▪ Fine process ▪ Cleaning
Distribution	-	-	-	-
Use	-	-	-	-
End-of-life	-	▪ Collection	▪ Collection	▪ Collection
Recovery	-	▪ Storage ▪ Disassembly ▪ Sorting ▪ Part-level test ▪ Cleaning	▪ Storage ▪ Disassembly ▪ Sorting ▪ Part-level test ▪ Cleaning ▪ Cladding ▪ Fine process	▪ Storage ▪ Disassembly ▪ Sorting ▪ (Back to material extraction and manufacturing stage)
Recovery option	**New**	**Reuse**	**Remanufacture**	**Recycle**

6.1.5 Input Data

The case study utilizes a combination of reliability test data collected from the industry partner and lab data from research laboratory. In the case of data that is inaccessible and unavailable from both the company and laboratory, intensive data collection is done on public available resources. The nature of data collected from company covers compressor specification, performance characteristics, part specification, wear analysis under different test conditions (eg. load test and temperature test), energy usage, cost and sales information. In order to gather a comprehensive set of data, additional data are obtained from credible source such as reports, scientific journals, scientific conference papers and electronic resources.

The selected model and series of compressor for this this case study is widely used in refrigerator, with the specification shows in Table 6-3. The particular type of compressor was chosen owing to the energy saving feature achieved large volume of unit sold. Therefore, there is substantial amount of return unit for recovery in future. Moreover, sufficient wear data are collected for reliability assessment. Wear data for five different capacities of compressor (with same model and series) under three test conditions (inTable 6-4) are collected for the chosen compressor. Compressor that goes through short duration test is equivalent to approximately 5 to 10 years of life span. On the other hand, long duration test is equivalent to approximately 10 to 20 years of life span.

Table 6-3 Compressor features

Model	Reciprocating type
Series	Inverter
Refrigerant	R600a
Cooling capacity	75 – 240 W
Gross weight	7.0 kg (including compressor oil)

Table 6-4 Compressor test condition

Test condition	**Test duration**	
	Short	**Long**
High temperature continuous run	500 hours	2000 hours
High load continuous run	500 hours	2000 hours
High load on/off run	50,000 cycles	170,000 cycles

Having established the required data sources, sub-components for each factor are identified, and actual figures subsequently obtained. Costing for raw part, energy, labour, machine depreciation, to name a few, are entered into the cost model constructed from the production process of these parts. These inputs can be found in Table 6-5, and all costs are expressed in Singapore dollar (S$). The data include the universal values (in Table 6-6) used to generate the disassembly cost in recovery activity, which will be applied in relevant scenario. During data collection, some data are limited and confidential. Thereby, some of the costs were generated and modified in order to remain confidentiality without affecting the accuracy of analysis. Data for old product collection, reuse and remanufacturing are not available in the company. Therefore, lab data has been used to estimate the costs spent in reuse and remanufacture.

Table 6-5 Universal input formula and values used in recovery process

Type	Value	Unit
Labor rate	r_l	dollar/hour
Energy cost	c_{elec}	$/kWh
Machine useful life	5	year
Fuel cost, c_{fuel} Fuel usage Fuel rate Fuel density	f_u x f_r f_u f_r 850	dollar/km liters/100km dollar/liter g/liter
Transportation cost Total distance	d x c_{fuel} d	dollar km
Number of recovery part, n_{rec}	2	

Table 6-6 Universal information used in product disassembly activity

Type	Time (hour)	Rate ($/hour)	Cost ($)	Remarks
Cut	t_{cut}	r_l	$(t_{cut}$ x $r_l)$ / n_{rec}	Higher n_{rec} causes lower cost
Dismantle	t_{dism}	r_l	$(t_{dis}$ x $r_l)$ / n_{rec}	Higher n_{rec} causes lower cost

6.2 Compressor Parts Characteristic Values

As mentioned in the previous section, block and crankshaft (in Figure 6-3) are analyzed in the case study. Before looking into recovery alternatives, decision maker has to know thoroughly the resources consumed in making new parts. This information is prime important to use as the benchmark for any recovery alternatives. The higher difference in value, the more resources saved from particular recovery alternative. Table 6-7 shows the information of block and crankshaft, which the specific type of material is undisclosed due to confidentiality. Both parts are casted; however, the complete parts go through different types of rough and fine processes.

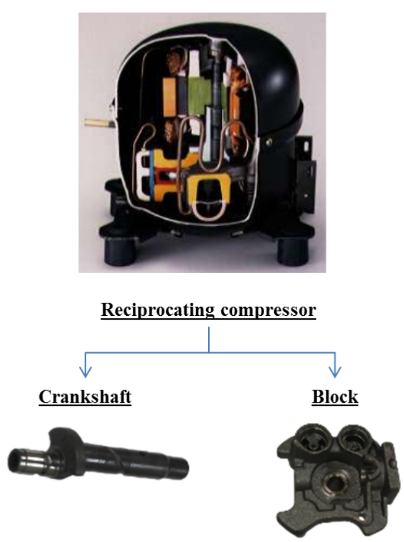


Figure 6-3 Compressor parts for recovery

Table 6-7 Part information

Specifications	Block	Crankshaft
Type of material	Gray cast iron	Ductile cast iron
Weight	~1.8kg	~0.3kg
Forming process	Casting	Casting
Rough process	Drilling, milling	Lathe, drilling
Fine process	Deburring, honing	Deburring, grinding

6.2.1 Time

Time is a performance indicator that measures the time spends in manufacturing a product, as well as the throughput of a manufacturing system. In some works, time spent is referred as lead time, manufacturing cycle time, throughput time or flow time. The process flow in Figure 6-4 and Figure 6-5 are referred for computing time of making new cylinder block and crankshaft. It covers virgin material extraction, casting, part machining, cleaning, coating and quality check. The time spent in manufacturing is examined closely as company could reduce the time it takes to deliver product to market. Moreover, it is highly relevant to operation cost, overhead cost and machine depreciation cost. For instance, the longer machining time is, the higher electricity and labor costs. Similarly, higher processing time incurs more electricity usage and then produces more emissions that is harmful to the environment. Thereby, time is worth studying and time minimization is always preferred because it is able to produce a given product more efficiently.

Gathering of time information from the company is limited, thereby the time value is gathered and calculated based on public available information. The total time per batch is estimated in order to meet current production facility and plan. Assumptions have been made in particular process.

- *Material extraction*: Time taken to extract a unit volume of block and crankshaft is equivalent to the extraction time for one working day. In fact, average world iron production per day is 3218 thousand tons, estimating based on monthly iron production published in World Steel Association website [144].
- *Casting process*: Melting time for one unit of part in casting process is estimated same as the batch of material melting time, which is 1000kg load per batch. Moreover, one unit part of shakeout time (part removal) is similar as mold (6 parts per mold) shakeout time.
- *Rough process*: All machining operations are fully automated.
- *Fine process*: Honing and deburring time is 30 seconds per unit according to the Brush Research Manufacturing [145].
- *Cleaning*: Cleaning time for one unit part is equal to cleaning time for one batch of part, with the batch size (loading capacity) of 90 units.
- *Coating*: Room temperature blackening is done in 3 minutes/unit according to the value published by Electrochemical Products Inc [146].
- *Quality check*: Final inspection is estimated for 30 seconds per unit.

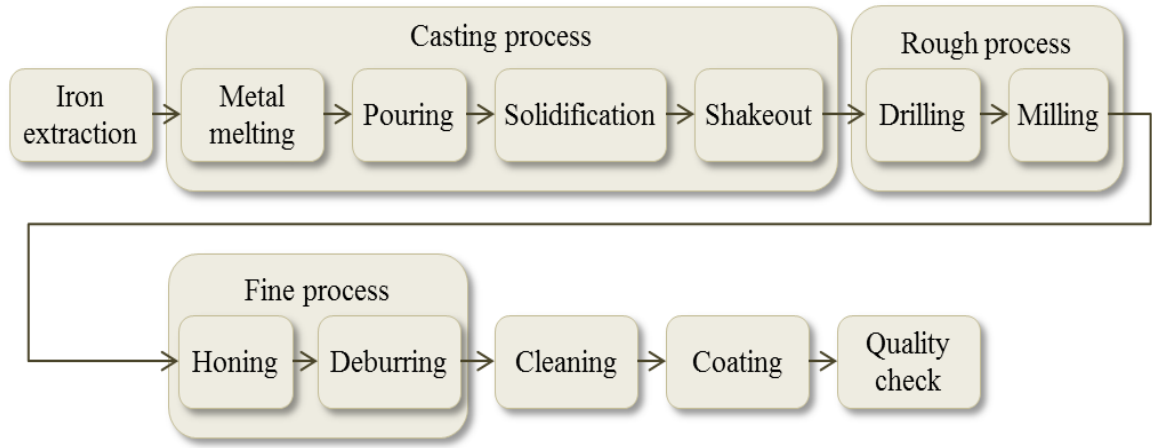


Figure 6-4 Process flow for making new cylinder block

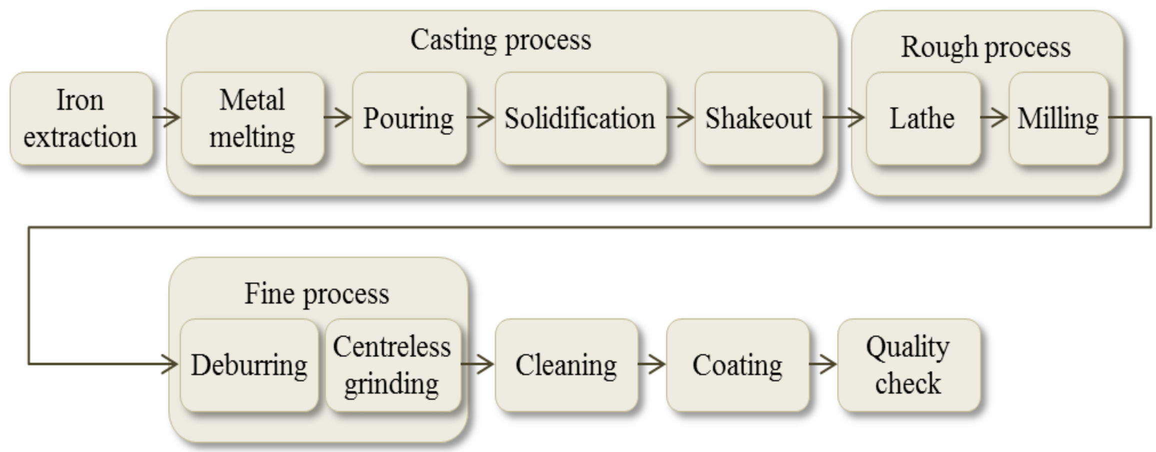


Figure 6-5 Process flow for making new crankshaft

6.2.2 Cost

The total casting cost is given as the sum of costs includes material, labor, energy, overheads and machine depreciation. The cost information provided by the company is in terms of total casting cost. However, the detailed calculation can be found in literature [147]. In order to protect the company's information, the costs are converted into percentage for this study, shows in Table 6-8. For instance, the material cost for crankshaft is approximately 30% of its final product and material cost for block is about

70% of the final product. This is because block has higher mass volume as compare to crankshaft. Besides, it informs that material cost is the major cost in making the part.

Table 6-8 Cost components of new part

Cost component		**Cost in percentage (out of total part cost)**	
		Crankshaft	**Block**
Operation, $\frac{c_{op_{new}}}{unit}$	Energy	12%	6%
	Expenses	7%	3%
	Direct labor	23%	8%
Overhead, $\frac{c_{oh_{new}}}{unit}$	Overhead	8%	7%
Procurement, $\frac{c_{proc_{new}}}{unit}$	Material	31%	70%
Machine depreciation, $\frac{c_{dep_{new}}}{n_{mfg(5)}}$	Machine depreciation	19%	6%
Total part cost, $\frac{c_{new}}{unit}$	$\frac{c_{op_{new}}}{unit}+\frac{c_{oh_{new}}}{unit}+\frac{c_{proc_{new}}}{unit}+\frac{c_{dep_{new}}}{n_{mfg(5)}}$	100%	100%

6.2.3 Environmental Impact

Building on the costing sub-components, relevant processes which incur environmental impact are singled out for the ensuing carbon footprint analysis. The main contributors to ecological burden are energy usage (in the form of electricity), fuel consumption and transportation mode and in virgin material extraction and part manufacturing (in Figure 6-6). The detail steps for part manufacturing include casting, lathe, drilling and milling.

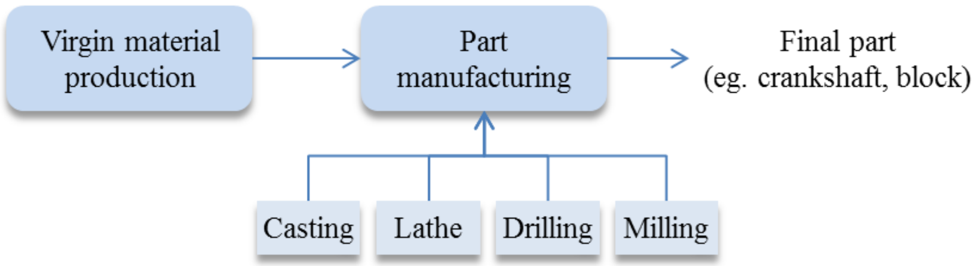


Figure 6-6 Manufacturing process flow that causes environmental impact

Inputs for the processes and sub-processes will be shown in the relevant scenario. In view of the inputs, the values counting on significance of environmental impact can be calculated. Firstly, the primary and secondary activity data are converted to GHG emissions by multiplying the activity data (d_{act}) by emission factor (f_e) for each activity. Secondly, the environmental impact is represented by multiplying the GHG emissions with the relevant global warming potential (GWP).

GHG emissions = $\sum (d_{act} * f_e)$

Unit mass CO_2e = $\sum$ (unit mass GHG * GWP)

The detail analysis is modeled using Simapro program, which the data for each of the reprocessing options are keyed into the program:

1. 1 kWh of electricity in Singapore is comprised of [148]:
   i. 0.758 kWh natural gas, burned in power plant
   ii. 0.219 kWh electricity, oil, at power plant
   iii. 0.023 kWh electricity, waste, at municipal waste incineration plant
2. Power consumed for recycling using induction furnace: 700 kWh/tonne [149]
3. Transportation used: Transport, lorry, 3.5-7.5 tonne, EURO 3

ReCiPe (midpoint) is utilised as the assessment method. And among the three cultural perspectives, Egalitarian is chosen for it represents long-term and conservative environmental mindset. Furthermore, the EI calculation is reflected in kg CO_2 equivalent, which is located under the “Climate Change” impact category [150]. In the end, the procedure generates various environmental impact indicators, as shown in Appendix C.

6.3 Scenario I: Recovery of Compressor Cylinder Block

6.3.1 Scenario Description

The first scenario is studying on the compressor cylinder block, which has the highest weight in the selected compressor. It is constructed in the size of about 12cm width by 12cm length and about 10cm in height. Cylinder block shows in Figure 6-7 is part of the compressing element (in Figure 6-3), constituting a chamber for fluid compression and bearing portion which support rotatable crankshaft. The fluid compression is created by a piston, where the piston is connected to crankshaft. The piston is inserted in the bore hole when crankshaft is rotating. A high accuracy of piston size and bore hole dimension are required to provide the right amount of compression pressure. In the reciprocating compressor, current flows through stator to generate magnetic field, therefore crankshaft that fixed to the rotor rotates. Under the continuous usage condition, the inner wall of bore hole could have gone through critical wear and tear as compare to other portion of block. Therefore, bore hole is identified as the critical damage area for the part. When the cylinder block is returned, the wear dimension of bore hole will be checked.

In this scenario, 42 samples consist in 5 models of block are received from production reject. Some of the blocks are rejected in assembly line, function fail in product test, unused after reliability test and part manufacturing defects. Cylinder block from the fail product is dismantled. Crankshaft that is tight fitted at the center hole has been damaged during the dismantling process.

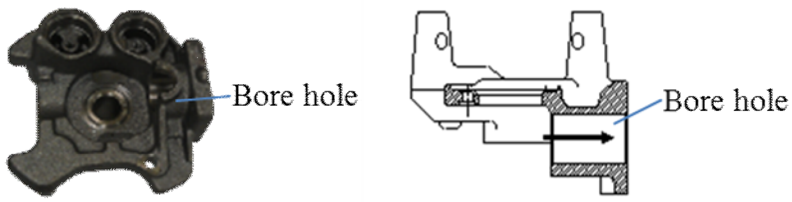


Figure 6-7 Top and side view of cylinder block

6.3.2 The Validation Outline

Cylinder blocks that are rejected in production house are validated using the assessment framework mentioned in Chapter 4. Figure 6-8 shows the assessment flow for cylinder block, where the rejected compressor will be dismantled and cylinder block will be singled out for defect identification. Otherwise, parts that are rejected from part production line will skip the dismantling step. The part will be measured at the critical damage area, then the measurements are compared to the specification. By recognizing the type of return channel, it skips the unnecessary reverse engineering effort on estimating the part condition. 42 samples of cylinder block have been validated using the framework.

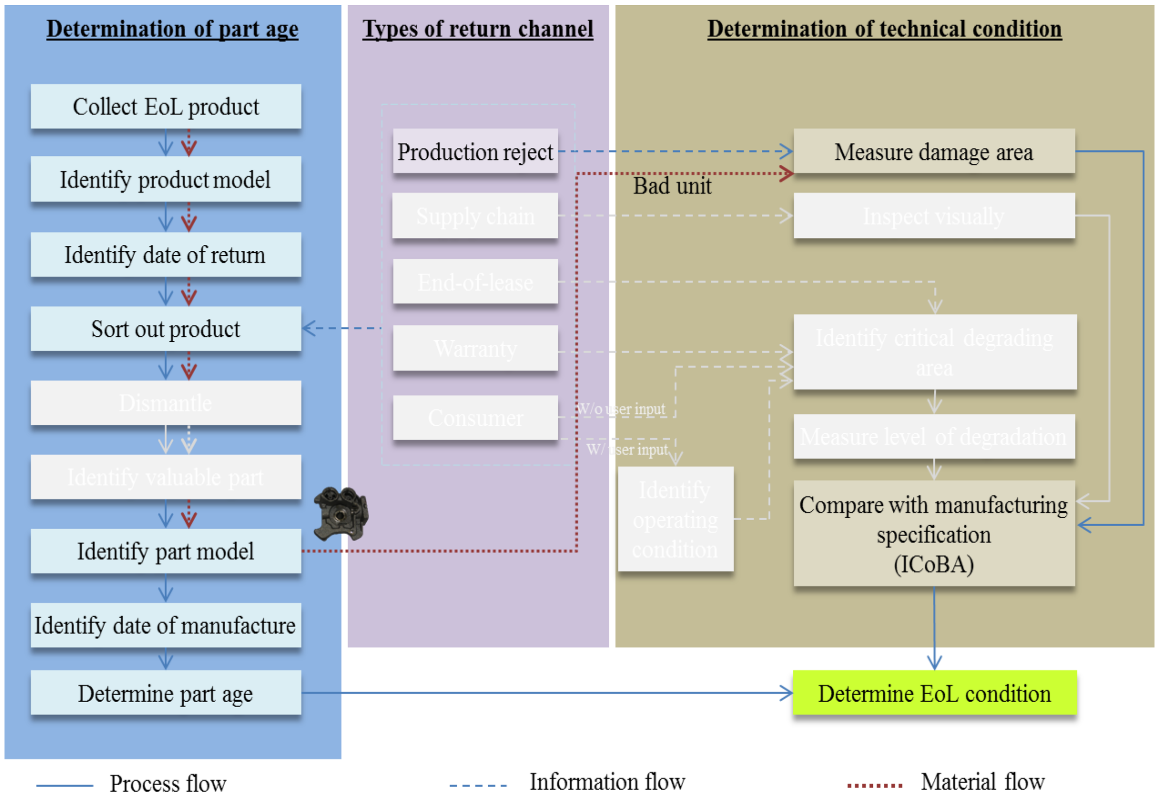


Figure 6-8 Cylinder block assessment based on return channel information

Knowing the type of defect, the block is going through further assessment in Figure 6-9. The part wear-out life is identified after the bore hole of cylinder block is measured. Then, the block wear-out dimension and life time are recorded and the results are plotted. The results listed in Table 6-9 and the plots in Figure 6-10 are the example for some of the part conditions. The threshold specification for inner wall wear for bole hole is 0.5µm. Parts that are returning from reliability study had gone through a certain period of operating cycle, and the measurement notified that there is minimal wear-out. During the assessment, it has been noticed that the rejected blocks are mainly damaged by the dismantling process. This is because of high force is applied to pull out the crankshaft in order to separate from cylinder block. Thereby, it causes abrasion at the inner wall of the center hole. Besides, the part life has reached the threshold life. In such case, the parts are inappropriate for reuse even though the bore hole is perfect. The part shall consider the recovery option between remanufacturing and recycling. This has led to figuring out the availability of remanufacturing technology for the part, which will be explained in the following paragraph. In this study, the block structure is inappropriate for remanufacturing. Thus, recycling will be the last option. The cleanliness check in this study is done via visual inspection. It is identified that the parts are in the cleanliness level 3. Recovery values in terms of time, cost and environmental impact are determined and explained in subsequent section.

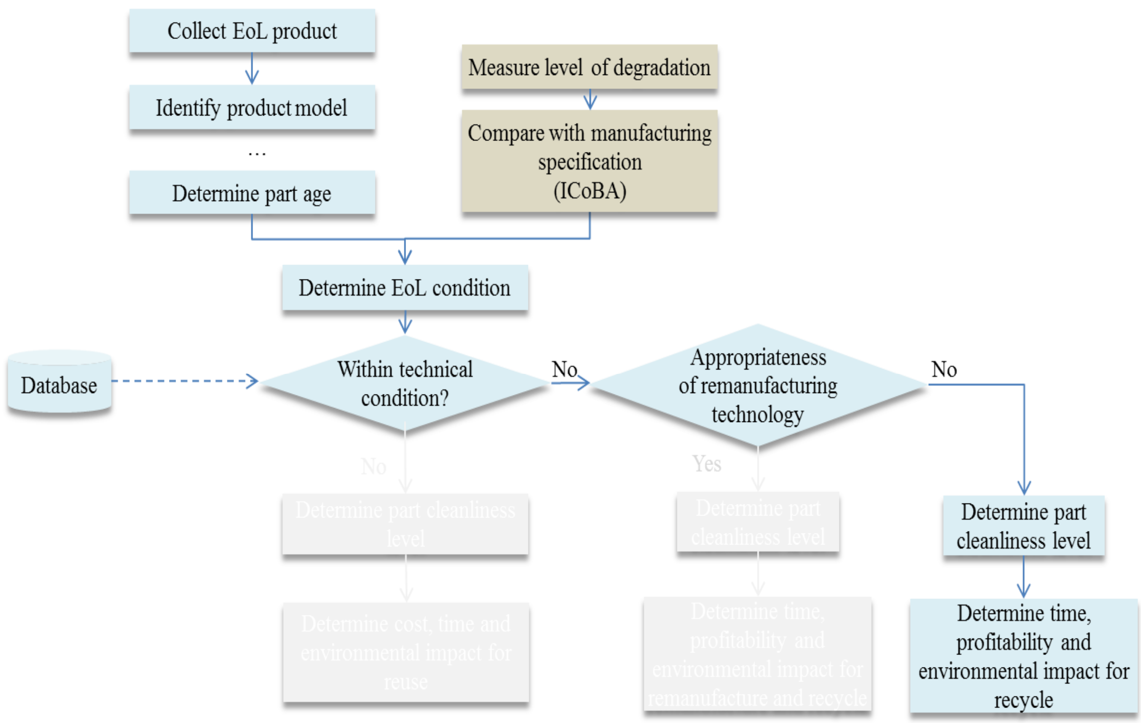


Figure 6-9 Assessment flow for cylinder block from production reject

Table 6-9 Part condition

Item number	Wear-out dimension	Life time	Remark
EYY-100E: 11	< Threshold dimension	At short cycle threshold	Surface scratch at inner wall of center hole
EYY-100E: 12	< Threshold dimension	At short cycle threshold	Surface scratch at inner wall of center hole
EYY-76E: 2	< Threshold dimension	At short cycle threshold	Surface scratch at inner wall of center hole
EYY-76E: 3	< Threshold dimension	At short cycle threshold	Surface scratch at inner wall of center hole
DKK43C: 15	New	0 cycle	Manufacturing defect
EKI120E: 1	< Threshold dimension	At short cycle threshold	Surface scratch at inner wall of center hole
etc.	…		…

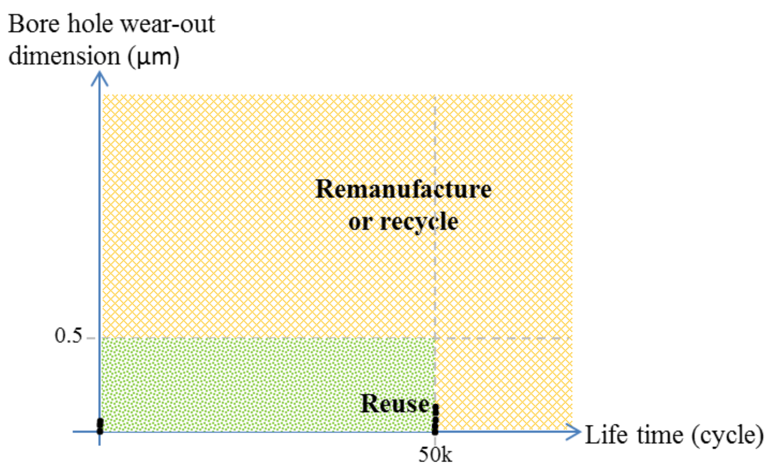


Figure 6-10 Categorization of part condition

6.3.3 Technology Availability and Recovery Flow

In view of the outcome generated from the assessment, manufacturer might need to explore the recovery option of remanufacturing and recycle. Figure 6-11 illustrates the process flow for remanufacturing cylinder block. Laser cladding (in Figure 6-12) is identified as the technique used in remanufacturing. It is a processing technique for adding one material onto the targeted surface of another in controlled manner. The cladding thickness can be controlled by designing cladding material composition or optimize laser processing parameter. In addition, this technique required minimal heat input, thus it resulted in limited distortion of the substrate and reduces the need for additional corrective machining.

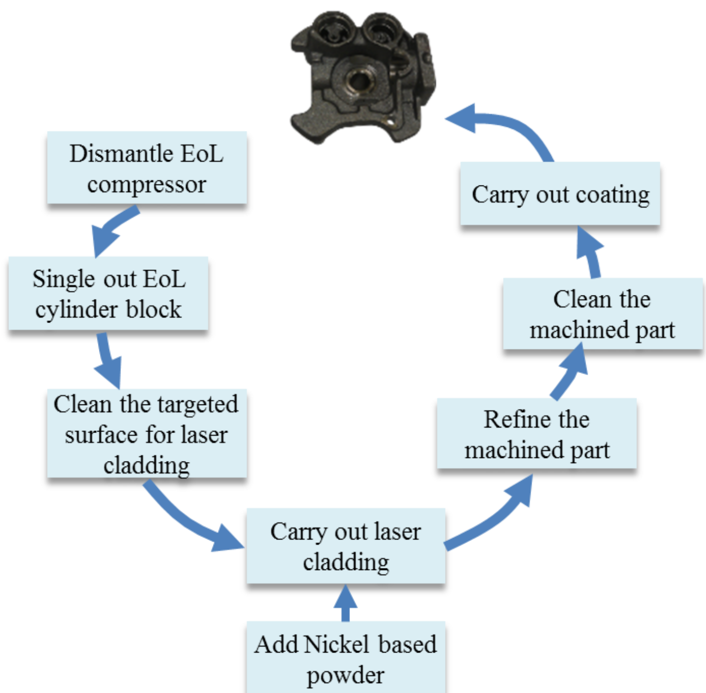


Figure 6-11 Remanufacturing process flow for cylinder block

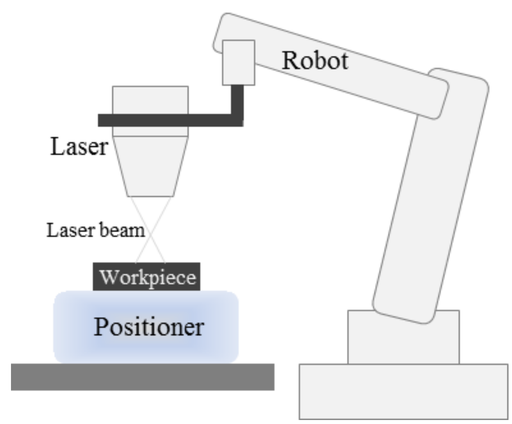


Figure 6-12 Laser cladding

Product recycling is a common practice in existing industry like glass, paper, plastic and metal. Closed-loop recycling is considered in this case study, where the recycled material is fed back to the manufacturing system to produce the same product. Figure 6-13 shows the process flow for part recycling, which the system still requires a portion of virgin material in making new part in order to maintain the cast iron quality.

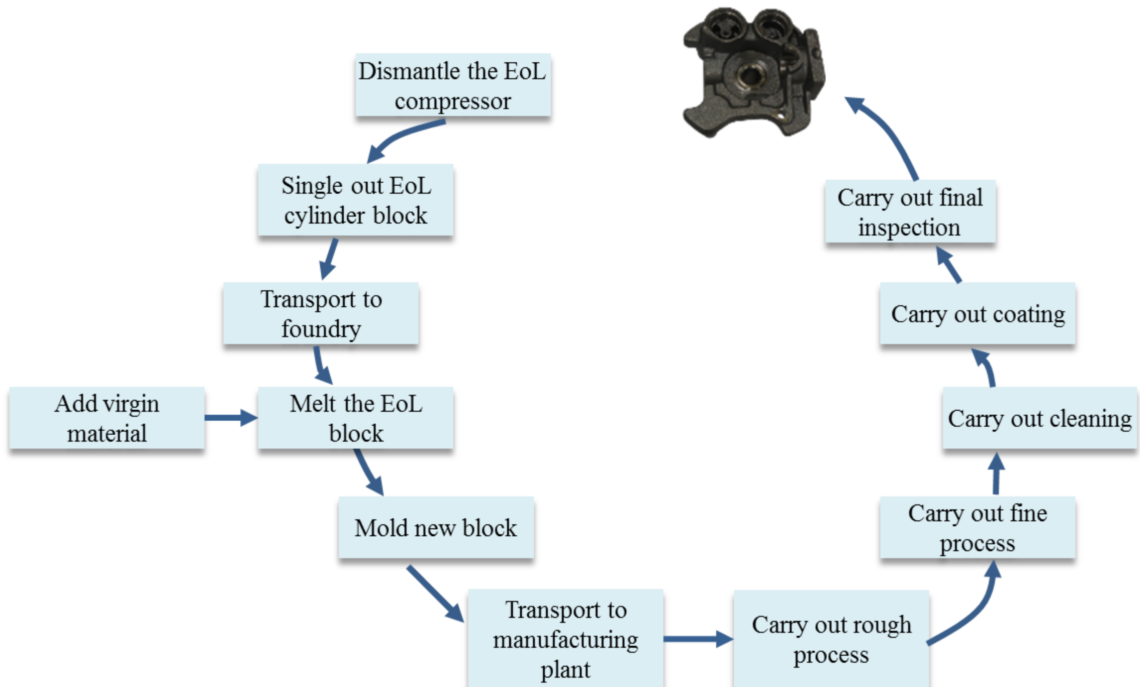


Figure 6-13 Recycling process flow for cylinder block

6.3.4 Model Implementation

From the assessment, the structure of cylinder block is unlikely to re-process by the current laser cladding technology. The bore and center hole does not have enough allowance space for the sizable laser nozzle. As a result, recycling is the only option in order to recover the material value. 60% of the recycled material will be fed as the input to manufacture a new cylinder block. In this study, the recovered value will be benchmarked to the resources spent in making new part. Value gains as compare to making new is termed as recovery value. Subsequent sections will explain time, cost and environmental impact models that assess the recycling value.

6.3.4.1 Time assessment

Based on the recycling recovery process in Figure 6-13, time spent in recovery activity is assessed. Some of the time information are measured based on real case, however, some are calculated using generated formulas from literature search. The measured and calculated data are listed in Table 6-10, and inputs for the formulas are showed below.

Transportation time, t_{trans} = 30 min/batch

Loading/unloading time, t_{load} = 30 min/batch per load

Cutting time, t_{cut} = 1 min/unit compressor

Dismantling time, t_{dism} = 3 min/unit compressor

Melting factor, f_m = 560kWh/ton

Furnace power, p_f = 700kW with 75% efficient

Volume of mold, V_{mold} = 301.37cm^3

Area of sprue gate, A_{gate} = 2.27cm^2

Volume of sprue gate, V_{gate} = 198.10cm/s

Mold cross sectional area, A_m = 100cm^2

Gate cross-sectional area, A_g = 1.77cm^2

Gravity, g = 981cm/s^2

Total height of sprue, h_t = 20cm

Height of mold, h_m = 10cm

Density of cast iron, ρ_c = 7300kg/m^3 [151]

Latent heat of solidification for Gray cast iron, ΔH_f = 96kJ/kg [152]

Cast iron melting temperature, T_m = 1149℃ [152]

Initial mold temperature, T_0 = 200℃

Thermal conductivity of sand, k_m = 0.6W/m-K [153]

Density of sand, ρ_m = 1500kg/m^3 [153]

Specific heat of sand, c_m = 1.16kJ/kgK [153]

Volume of cavity, V = 0.0003m^3

Area of cavity, A = 0.04m^2

Length of tool travel, L = 2.3622inch

Feed rate, s_r = 0.011inch/rev [154]

Revolution per minute, rpm = 458 [154]

Length of cut, L_{cut} = 17.06m

Feed/min. = 36.75m/min [154]

Number of cut, n = 4

Table 6-10 Input data and formulas for time spent

Time component	Measure and formula	Making new, t_0	Recycling, t_3
Transport, t_{trans}	$t_{trans} + t_{load}$	-	**90min/batch**
Disassembly, t_{dis}	$\frac{t_{cut}}{unit} + \frac{t_{dism}}{unit}$	-	**2 min/unit**
Cut, $\frac{t_{cut}}{unit}$	$\frac{t_{cut}}{n_{rec\_c}}$	-	0.5min/unit
Dismantle, $\frac{t_{dism}}{unit}$	$\frac{t_{dism}}{n_{rec\_c}}$	-	1.5min/unit
Iron extraction, t_{ext}	1 day	**480 min/batch**	**480 min/batch**
Casting, t_{cast}	$t_{melt} + t_{pour} + t_{sol} + t_{shake}$	**65.55 min/batch**	**65.55 min/batch**
Melting, t_{melt}	$\frac{fm}{p_f} * 60$	64.00 min/batch	64.00 min/batch
Pouring, t_{pour}	$t_{mold} + t_{gate}$	0.16 min/unit	0.16 min/unit
Mold filling, t_{mold}	$\frac{V_{mold}}{A_{gate}V_{gate}}$	0.03 min/unit	0.03 min/unit
Gate filling, t_{gate}	$\frac{2A_m}{A_g\sqrt{2g}}(\sqrt{h_t}-\sqrt{h_t-h_m})$	0.13 min/unit	0.13 min/unit
Solidification, t_{sol}	$\left[\frac{\pi}{4}\left(\frac{\rho_c \Delta H_f}{T_m - T_0}\right)^2 \frac{1}{k_m \rho_m c_m}\right]\left(\frac{V}{A}\right)^2$	0.39 min/batch	0.39 min/batch
Removal, t_{shake}	1min/mold	1.00 min/batch	1.00 min/batch
Rough process, t_{rough}	$t_{drill} + t_{mill}$	**3.74 min/unit**	**3.74 min/unit**
Drilling, t_{drill}	$\frac{L}{s_r \times rpm}$	1.88 min/unit	1.88 min/unit
Milling, t_{mill}	$\frac{L_{cut}}{Feed/Min.} \times n_{cut}$	1.86 min/unit	1.86 min/unit
Fine process, t_{fine}		**0.5 min/unit**	**0.5 min/unit**
Honing+Deburring	30 sec/unit		
Cleaning, t_{clean}		**40 min/batch**	**40 min/batch**
Coating, t_{coat}	3 min/unit	**3 min/unit**	**3 min/unit**
Quality check, t_{check}	30sec/unit	**0.5 min/unit**	**0.5 min/unit**
Total time		**593.29 min/unit**	**685.29 min/unit**

6.3.4.2 Cost assessment

Recycling material flow diagram is shown in Figure 6-14, where recycling rate (R_2) is the number of production reject. In this study, the amount of annual production of particular model is 4 million units. The recycling rate is estimated based on the average monthly reject. R_1 is the portion of recycled material that is fed back to the manufacturing, which is set as 60%. The remaining material constitutes of virgin material. Cost for cylinder block is calculated using the equation listed in Table 6-11, which the cost components consist of material cost, machining expenses in operation cost, overhead, transportation and machine depreciation cost. Collection cost for end-of-life cylinder block is not applicable in this scenario as all the blocks are returning from production. The input figures are listed below. Cost of resources may vary for each purchase over 1 year. However, latest unit price of material (July 2014), unit price of electricity tariff (July 2014) and unit price of fuel (August 2014) are taken in the calculation.

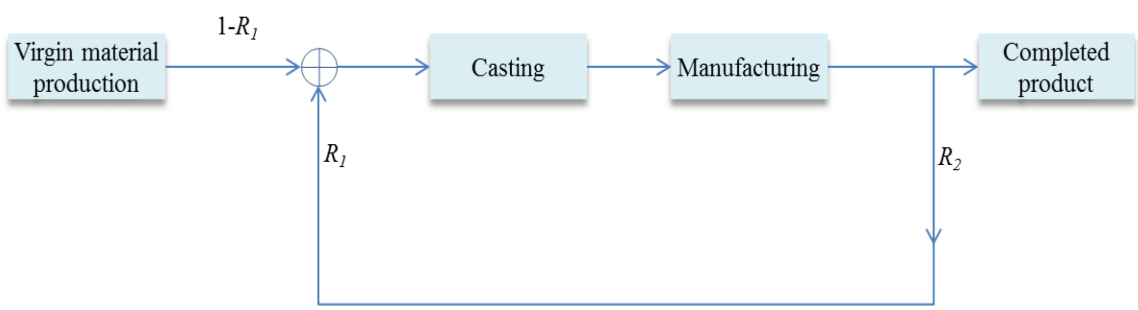


Figure 6-14 Material flows for recycling process

Number of manufacturing unit, n_{mfg} = 4,000,000

Unit weight of block, w_{bpu} = 1.8kg

Unit cost of material, c_{mpu_i} = \$0.12/kg (i = cur)

Defect rate, r_{def} = 0.01

Metal loss in melting, f_1 = 1.07 [155]

Metal loss in pouring, f_2 = 1.04 [155]

Metal loss in frettling, f_3 = 1.04 [155]

Total electricity usage in manufacturing process per unit part, $\sum Elec_{proc\_k}$ = 2.329kWh/unit

Unit cost of electricity, c_{elec_i} = \$0.2345/kWh (i = cur)

$Distance_j$, = 40km (j = 1 is new)

$Distance_j$, = 80km (j = 3 is recycling)

Unit Cost of fuel, c_{fuel_i} = \$0.24/km (i = cur)

Number of unit per truck, n_{truck} = 13200

Proportion of recycled material used in new part, R_1 = 0.6

Rejection rate, R_2 = 0.001

Table 6-11 Input formulas for cost calculation

Cost component	Formula	Making new, c_0	Recycling, c_3
Operation cost, c_{op_j}	$c_{mat\_j} + c_{process\_j} + c_{labor\_j}$	**\$1.10/unit**	**\$0.920/unit**
Cost of material, c_{mat_0}	$\frac{n_{mfg} \times (1+r_{def}) \times w_{bpu} \times f_1 \times f_2 \times f_3 \times c_{mpu\_i}}{n_{mfg}}$	\$0.252/unit	-
Cost of material, c_{mat_3}	$c_{mpu\_i} \times \frac{w_{bpu}}{w_{total}}$	-	\$0.072/unit
Total weight of material, w_{total}	$w_v + (R_2 \times n_{mfg} \times w_{bpu})$	-	10080kg
Total weight of virgin material, w_v	$(1 - R_1) \times R_2 \times n_{mfg} \times w_{bpu}$	-	2880kg
Cost of process, $c_{process\_j}$	$\frac{\sum_{k=1}^{n} Elec_{proc\_k} \times c_{elec\_i}}{n_{mfg}}$	\$0.546/unit	\$0.546/unit
Cost of labor, c_{labor_j}		\$0.302/unit	\$0.302/unit
Overhead cost, c_{oh_j}		**\$0.392/unit**	**\$0.392/unit**
Transportation cost, c_{proc_j}	$\frac{Disatance_i \times c_{fuel\_i}}{n_{truck}}$	**\$0.0007/unit**	**\$0.0014/unit**
Machine depreciation cost, c_{dep_j}		**\$0.342/unit**	**\$0.342/unit**
Total cost		**\$1.84/unit**	**\$1.66/unit**

6.3.4.3 Environmental impact assessment

Environmental burden generated from cylinder block recycling is assessed based on the flow shows in Figure 6-15. The environmental impact caused in the system is modeled using SimaPro, focusing on the carbon footprint aspect. Upstream production is included in the model. The environmental impact of recycling option is modeled based on the information in Table 6-12. In this scenario, environmental impact caused in production of 40% virgin material required by recycling line has same amount of environmental impact caused in production of 100% virgin material. The assessment results are showed in Table 6-12, which recycling of a unit cylinder block has higher carbon emission than manufacturing of new block.

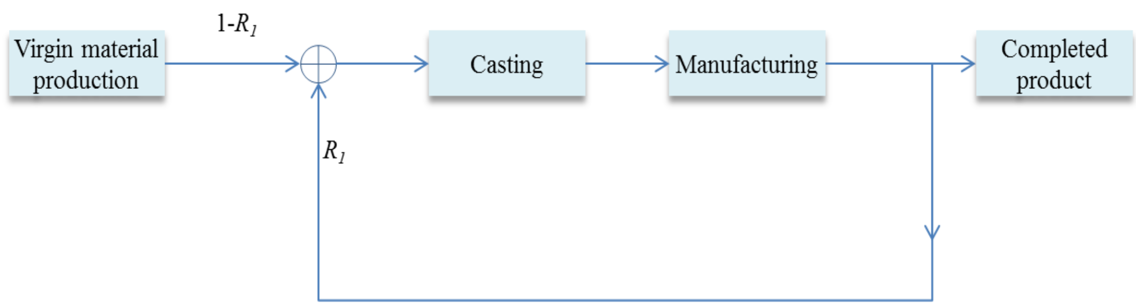


Figure 6-15 Environmental impacts generate in recycling activities

Table 6-12 Input information for calculating carbon emission

Environmental impact component	Formula	Making new, EI_0	Recycling, EI_3
EI_{op_0}	(EI. of material extraction + EI. of casting + EI. of rough process + EI. of fine process + EI. of transportation) per unit	3.307kgCO_2eq/unit	
Ei_{op_3}	(EI. of disassembly + EI. of material extraction + EI. of casting + EI. of rough process + EI. of fine process + EI. of transportation) per unit		3.309kgCO_2eq/unit

6.3.5 Decision Analysis

The decision for this scenario is straight forward after going through the assessment. Recycling is the only option for part recovery, given take-back regulation is enforced. However, further analysis using utility theory is performed in order to determine and observe the overall benefit as compare to manufacturing a new part.

After the detailed estimation on time spent in the previous section, the maximum and minimum limits are established and utility curve is plotted in Figure 6-16. The maximum time spent is mainly due to delay along the production proceaa. Five common delays in production are listed in Table 6-13. An estimated delay period is given and the frequency of occurrence is counted within a year. Subsequently, the total delay in a year is summed up that resulted in total delays. The total operation time has considered half of the automated manufacturing processes that operate 24 hours and the other half operations run only 8 hours a day. Then, the delay ratio is computed using formula (in Table 6-13), which the ratio is used as the delay factor in determining maximum time limit. Information in Table 6-14 computes the threshold limit for time spent in part recovery process. Reuse of part spent least time among all options. Besides, number of part for recovery (n_{rec}) is the main factor affecting the time spent in product disassembly. The more parts in a product are recovered, the lower disassembly time benefits from sharing out the cutting and dismantling time among the parts. In this scenario, an optimistic estimation of 20% of the part in compressor will be recovered. As such, taking 20 recovery parts into reuse option set up the minimum limit. On the contrary, considering 1 recovery part with the delay in recycling option set the maximum limit. Time spent in making new part is specified as the mid value ($x_{0.5}$) for indifference preference between saving 410.29 min/unit or spending addition 133 min/unit. This is followed by calculating $z_{0.5}$ using Equation (6-1) and look up the table (in Appendix C1) to find out corresponding normalized exponential constant, R_{time}. Then, ρ_{time} is computed with Equation (6-2). A concave shape utility curve indicates risk averse attitude. Value that is below 183 obtains utility of one, on the other hand, value above 726.29 has zero utility.

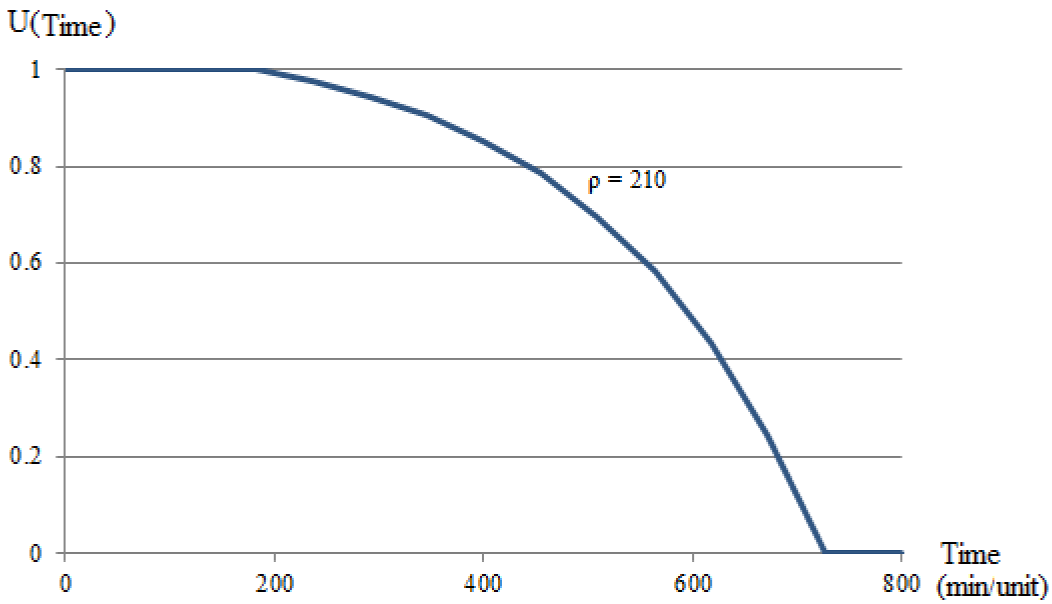


Figure 6-16 Utility function curve for time

Table 6-13 Key parameters and input formulas for production delay

Key parameters, p_i	**Delay period (min), d_i**	**Frequency, $freq_i$**	***Total delay (min)***
Equipment breakdown, p_1	60	12	720
Short of raw material, p_2	1440	3	4320
Short of consumable, p_3	1440	3	4320
Short of manpower, p_4	480	12	5760
Power shutdown, p_5	30	1	30

Total delay per year	$\sum_{i=1}^{5} d_i \cdot freq_i$	15150 min
Total operation time per year	0.5 x 12(m) x 20(d) x 24(h) + 0.5 x 12(m) x 20(d) x 8(h)	230400 min
Delay ratio	Total delay per year/ Total operation time per year	7%

Table 6-14 Threshold calculation for time

Threshold for time	Calculation	Value
$t_{min} = t_1$		183 min/unit
$t_1\|_{n_{rec}=20}$	183 min/unit	
t_{max}	$t_3\|_{n_{rec}=1,\,Delay}$	726.29 min/unit
$t_3\|_{n_{rec}=1}$	683.28 min/unit	
Delay	7% of t_0	

Table 6-15 Input data for generating time utility function curve

Input	Value
Maximum time, at $u(t_{max}) = 0$	183 min/unit
Minimum time, at $u(t_{min}) = 1$	726.29 min/unit
Midvalue, $x_{0.5} = t_0$	593.29 min/unit
R_{time}	0.387
Risk tolerance, ρ_{time}	210

$$\frac{H - x_{0.5}}{H - L} = z_{0.5} \tag{6-1}$$

$$\rho = (H - L)R \tag{6-2}$$

Cost utility function is plotted in Figure 6-17, with the input information listed in Table 6-16 and Table 6-17. As refer to Table 6-16, the highest and lowest values for key variables are taken from historic data published by the authority. Costs of raw material (iron ore) are referring to the material price chart for 4 years period from January 2010 to July 2014 [156]. The unit cost of electricity is referring to Singapore electricity tariff for High Tension Large (HRL) supplies in between January 2010 to July 2014 [157]. And the cost of fuel refers to Singapore petro fluctuation chart from July 2011 to August 2014

[158]. Number of part for recovery (n_{rec}) is identified as key variable because it largely influences on total recovery cost, especially cost of disassembly. The more parts are recovered, the lower disassembly cost is. In this scenario, an optimistic estimation of 20% of the part in compressor will be recovered. After gathering all the minimum and maximum values, minimum and maximum cost can be identified. Taking all the minimum values in reuse option generate the minimum limit. The minimum limit is most favorable, thus it is assigned as utility value of 1. In the case of any recovery solution spends below the minimum limit, the utility value holds 1. On the other hand, all the maximum values apply in recycling option give maximum limit. The maximum limit sets the limit of maximum cost spent in recovery. Any cost spent above this value is recognized as zero utility. Cost of making new part is identified as the mid value ($x_{0.5}$) which specifies indifference in saving \$0.88/unit or spending more \$0.67/unit. This is followed by determining $z_{0.5}$ using Equation (6-1) and ρ_{cost} value using Equation (6-2). With all the inputs, the utility function curve that takes into consideration on cost spent in all recovery options is plotted. The nearly straight curve implies low degree of risk aversion.

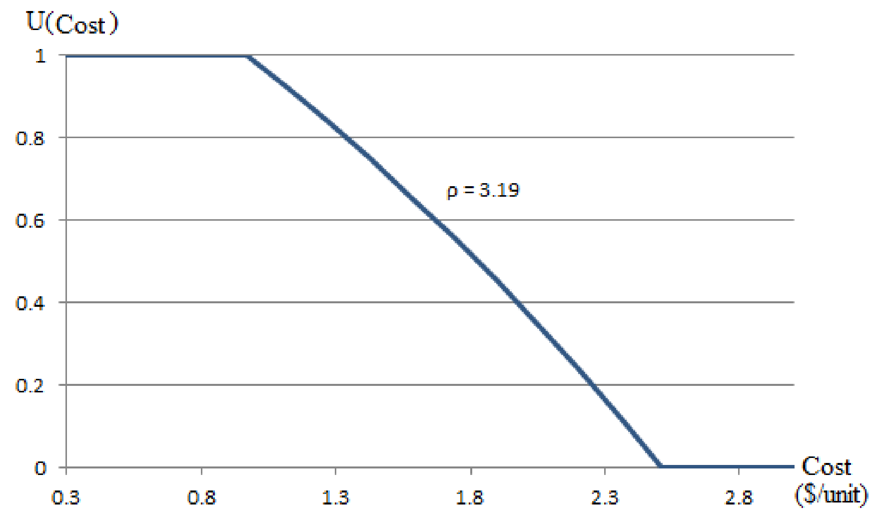


Figure 6-17 Utility function curve for cost

Table 6-16 Key variables in threshold limit determination

Key variable	Unit	Minimum value, *i*=min	Current value, *i*=cur	Maximum value, *i*=max
Cost of raw material, c_{mpu_i}	$/kg	0.1180	0.1200	0.2590
Cost of electricity, c_{elec_i}	$/kwh	0.2076	0.2345	0.2721
Cost of fuel, c_{fuel_i}	$/km	0.2250	0.2503	0.2548
Number of recovery part, n_{rec_i}	unit	20	2	1

Table 6-17 Threshold calculation for cost

Threshold for cost	Calculation	Value
c_{min}	$c_1\|_{n_{rec}=20,\ i=\text{min}}$	$0.96/unit
c_{max}	$c_3\|_{n_{rec}=1,\ i=\text{max}}$	$2.51/unit

Table 6-18 Input data for generating cost utility function curve

Input	Value
Maximum cost, at $u(c_{max}) = 0$	\$2.51/unit
Minimum cost, at $u(c_{min}) = 1$	\$0.96/unit
Midvalue, $x_{0.5} = c_0$	\$1.84/unit
R_{cost}	2.063
Risk tolerance, ρ_{cost}	3.19

Lastly, utility function curve for environmental impact using carbon emission as indicator is plotted in Figure 6-18, using the information listed in Table 6-19 and Table 6-20. From the analysis, carbon emission from making new part is set as the maximum limit. This is because current level of environmental quality is unpromising as reported by National Environmental Policy Act (NEPA). In other words, emission above the maximum limit is unfavorable at all, thus the values shall assign as zero utility. On the other hand, carbon emitted from reuse recovery activity is set as the lowest limit. Corresponding to the environmental act, Singapore government has pledge on yearly reduction of carbon emission by 3.6%. As such, the reduction of 3.6% from business as usual block production is set as mid value ($x_{0.5}$). This value indicates the indifference between save in 2.965kgCO_2eq carbon emits and extra emission for 0.119kgCO_2eq. The risk tolerance (ρ_{EI}) for carbon emission indicator is calculated using Equation (6-2). Given the minimum, maximum and mid value, the plotted curve illustrates risk adverse trend. In this case, the small value of ρ demonstrates high degree of aversion.

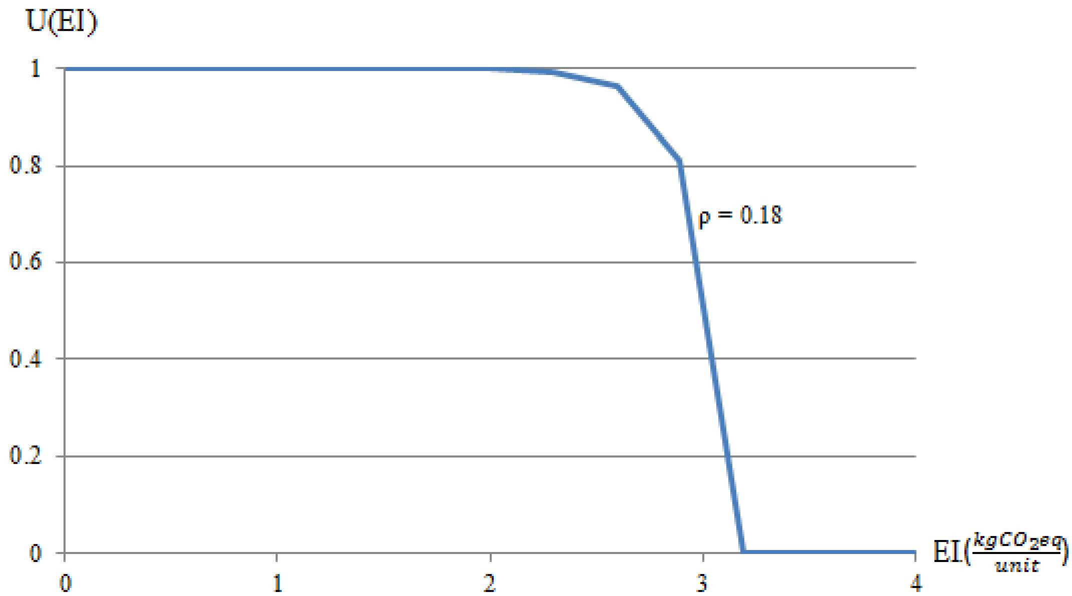


Figure 6-18 Utility function curve for carbon emission

Table 6-19 Threshold calculation for carbon emission

Threshold for carbon emission	**Value**
$EI_{min} = EI_1$	0.223kgCO_2eq/unit
$EI_{max} = EI_0$	3.307kgCO_2eq/unit

Table 6-20 Input data for generating carbon emission utility function curve

Input	**Value**
Maximum carbon emission, at $u(EI_{max}) = 0$	3.307kgCO_2eq/unit
Minimum carbon emission, at $u(EI_{min}) = 1$	0.223kgCO_2eq/unit
Midvalue, $x_{0.5} = (1\text{-}0.036)*EI_0$	3.188kgCO_2eq/unit
R_{EI}	0.058
Risk tolerance, ρ_{EI}	0.179

In order to complete determination of the value function for part recovery, it is necessary to find out the weights w_1, w_2 and w_3 for the three attributes. Pairwise comparison is one of the simple and systematic ways to determine weights. However, each user may have varying preference over certain attribute and thus bias could occur in decision making. Conveniently, comparison of the utility curves indirectly provides an insight on significance of the attribute. Review the utility curves of cost (in Figure 6-17) and carbon emission (in Figure 6-18) above are about in the same range. Comparing the ρ value indicates the degree of aversion, which lower ρ signifies higher degree or risk aversion. $\rho_{EI} < \rho_{cost}$ gives an insight on environmental impact attribute is more important than cost. However, time and cost have large different on the measuring scale. Calculating the gradient of curve is proposed to identify significance between the two attributes. Calculations in Table 6-21 shows that the gradient of cost is higher than time, therefore it can be concluded that cost is more important than time. Overall, the degree of adversity is arranged in the order of EI > Cost > Time.

Table 6-21 Gradient calculations for time and cost utility function

Attribute	**Time**		**Cost**	
	U(Time)	Gradient	U(Cost)	Gradient
	1	0.000443	1	0.515487
	0.97593	0.000574	0.920372	0.54109
	0.944762	0.000743	0.836789	0.567964
	0.904405	0.000962	0.749054	0.596173
	0.852149	0.001245	0.656962	0.625783
	0.784484	0.001613	0.560297	0.656864
	0.696868	0.002088	0.45883	0.689489
	0.583418	0.002704	0.352323	0.723734
	0.436517	0.003501	0.240526	0.75968
	0.246301	0.004534	0.123177	0.797411
	0		0	
Average		**0.001841**		**0.647368**

According to Saaty's intensity of importance scale (Appendix A1), environmental impact is approximated as 3 times more important than cost and 9 times more important than time. Besides, the cost is 5 times more important than time. Pairwise comparison is performed using the scale, as shown in Table 6-22. For instance, the first attribute in first column is compared to the attributes listed in first row each at a time. Then, an ***A***-matrix is generated based on the comparison table.

Table 6-22 Input for pairwise comparison

	Time, c_1	**Cost, c_2**	**Environmental impact, c_3**
Time, c_1	1	1/5	1/9
Cost, c_2	5	1	1/3
Environmental impact, c_3	9	3	1

Then, an ***A***-matrix is generated based on the comparison table.

$$\boldsymbol{A} = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{9} \\ 5 & 1 & \frac{1}{3} \\ 9 & 3 & 1 \end{bmatrix}$$

Rewrite the matrix into equations such that determinant of the coefficient matrix is zero.

$$Det(A - \lambda I) \begin{vmatrix} 1-\lambda & \frac{1}{5} & \frac{1}{9} \\ 5 & 1-\lambda & \frac{1}{3} \\ 9 & 3 & 1-\lambda \end{vmatrix} = 0$$

$$(A - \lambda I)\boldsymbol{w} = 0 \rightarrow \quad (1-\lambda)w_1 + \frac{1}{5}w_2 + \frac{1}{9}w_3 = 0$$

$$5w_1 + (1-\lambda)w_2 + \frac{1}{3}w_3 = 0$$

$$9w_1 + 3w_2 + (1-\lambda)w_3 = 0$$

Solving the above equations gives $w_1 = 0.064$; $w_2 = 0.267$; $w_3 = 0.669$. Finally, the total utility $u(j)$ can be computed using Equation (3-3) . The decision tree diagram is illustrated in Figure 6-19, which it clearly shows that recycling option has the higher utility value as compare to making new. Thereby, the decision shall be made based on the higher utility value.

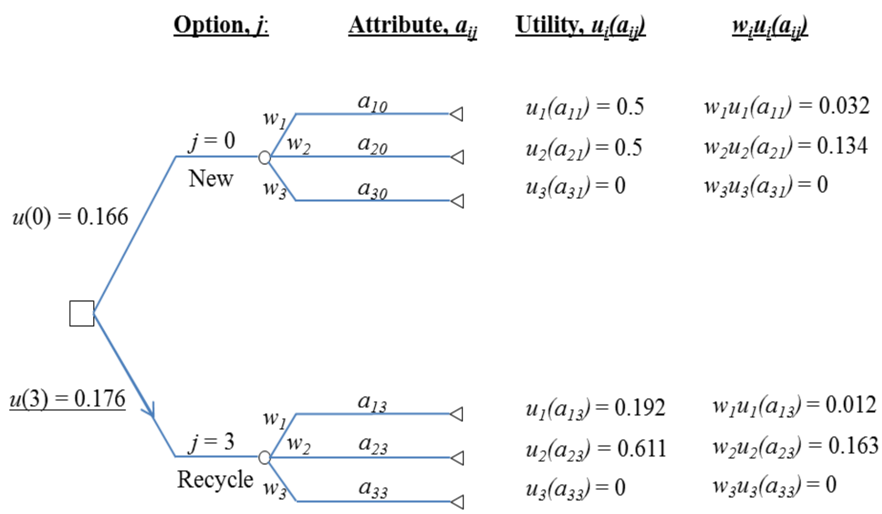


Figure 6-19 Decision tree for cylinder block recovery

6.3.6 Remarks of the First Scenario

The above scenario demonstrates the developed assessment framework and models are useful for supporting product recovery decision making process. The selection of threshold value is critical for determining the reusability potential of the EoL products. Therefore, manufacturers have to include as comprehensive component as possible in establishing the right threshold in order to accommodate the company's interest.

The time analysis adds a new dimension on the dynamic of production. It informs the knowledge needed for resource planning for future study. In addition, the cost profile generated at the end of the calculations can be used further analysis to detect any possibility of improvement. Cost exercise would increase the EoL product recovery from time, economic and environmental point of view in future. Also, the analysis reveals that including environmental aspect into the assessment strengthens the superiority of recycling. Overall, the outcome is confirmed to be useful to provide insights in decision making process.

The outcome of the scenario is summarized in Table 6-23. From the analysis, the results point out extra resources spent in time and carbon emission but gain in cost for block recycling. Reviewing the values, decision maker might judge the circumstances based on one gain out of three attributes. Block recycling should be the worse than making new. However, the decision is erroneous and unjustified. Thereby, utility value plays a key role in standardizing the calculated values across all attributes with different measure. Lastly, allocation of weights implies the manufacturer interest on particular performance. Comparing the total utility value of one option over another, block recycling can be decided undeniably.

Table 6-23 Summary of cylinder block recovery

	Time, a_{1j} (min/unit)	$u_1(a_{1j})$	w_1	**Cost, a_{2j} ($/unit)**	$u_2(a_{2j})$	w_2	**EI, a_{3j} (kgCO_2eq/unit)**	$u_3(a_{3j})$	w_3	**Total,** u**(j)** = $\sum_{i=1}^{3} w_i \cdot u_i(a_{ij})$
New, j=0	593.28	0.5	0.064	1.84	0.5	0.267	3.307	0	0.669	0.166
Recycle, j=3	685.28	0.19	0.064	1.66	0.61	0.267	3.309	0	0.669	0.176
Δ (3 – 0)	**(92)**			**0.18**			**(0.002)**			**0.010**

6.4 Scenario II: Recovery of Compressor Crankshaft

6.4.1 Scenario Description

The second scenario is studying on recovery of compressor crankshaft, which is one of the parts with substantial amount of material weight in the selected compressor. It is constructed in the size of about 15cm long and 2cm wide of rod diameter. Crankshaft shows in Figure 6-20 is part of the compressing element (in Figure 6-3), consist of main shaft and eccentric shaft. The main shaft is fixed at the rotor, when current flows through stator to generate magnetic field, rotor rotates the crankshaft. Piston that is connected to the eccentric shaft reciprocates in cylinder block. Thus, compression of fluid happens subsequently. The crankshaft rotation is continuously operating in household refrigeration compressor. Under continuous usage condition, the edge of the main shaft rod and eccentric shaft rod (as circled in the crankshaft drawing) are going through critical wear and tear. When the edge has worn out, the pressure for compression varies. A high accuracy of shaft dimension is required to provide the right amount of compression pressure. Therefore, two areas are identified as the critical damage portion for crankshaft. When the crankshaft is dismantled, the wear dimension at the identified area will be checked using profiler meter. The stylus of the profiler meter measures the dimension of main shaft edge towards right direction. And the eccentric shaft edge is measured towards the left direction.

In this scenario, 42 samples consist of 5 models of crankshaft are dismantled from end-of-life usage. Owing to technical experiment constraint, EoL compressors under studied are the compressors that already ran through short and long cycle for reliability test in production. In fact, the tested compressor ran more cycles than the designed life.

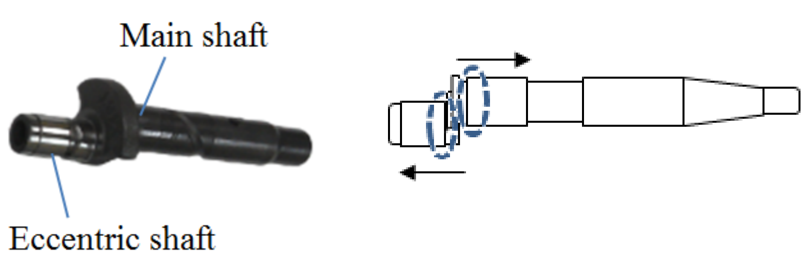


Figure 6-20 Actual and drawing of compressor crankshaft

6.4.2 Validation outline

The EoL parts are then validated using the assessment framework mentioned in Chapter 4. Figure 6-21 shows the assessment flow for crankshaft, where the EoL parts will be checked through the steps. In this case, the operating condition of the compressor is operated under normal condition. This information aid in estimating part used life more accurately when it refers to the design specification. Then, the part is identified for the critical wear out area, followed by measure the level of wear out. Lastly, compare the measurement results to design specification. 42 samples of crankshaft have been validated using the framework.

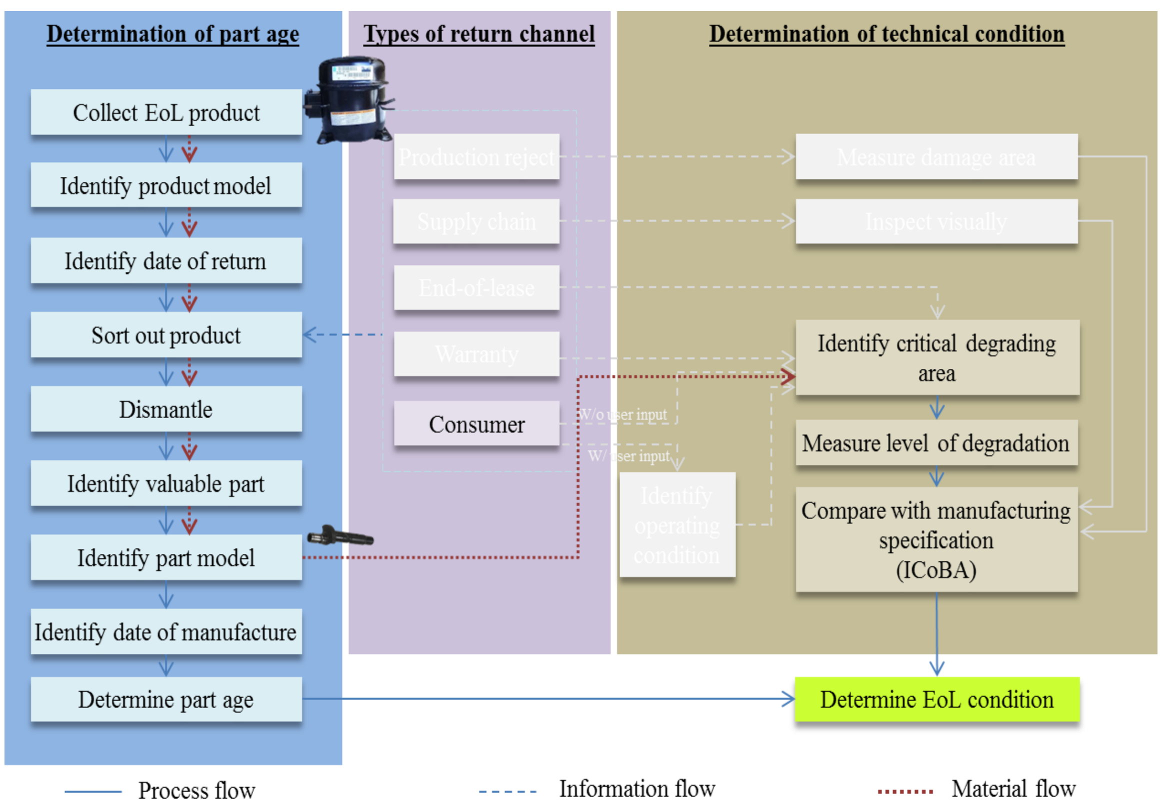


Figure 6-21 Crankshaft assessment based on return channel information

After knowing type of defect, the crankshaft is going through further assessment as shown in Figure 6-22. The part wear-out life is identified after the wear out of main and eccentric journal are measured. Then, the crankshaft wear-out dimension and life time are recorded and the results are plotted. The results listed in Table 6-24 and the plots in Figure 6-23 are the example for some of the part wear out life. The threshold specification for the shaft journal is 3μm. It has been notified from the part measurement that there is minor wear out at both the journals although the parts had operated above the designed life. Thereby, the parts cannot be considered for reuse even though the wear out dimension does not reach the specification. This is followed by checking the suitability of part for remanufacturing. For instance, small and deep hollow structure is inaccessible for current laser nozzle technology. However, the shape of the studied crankshaft journal is perfectly fine using laser cladding technology. The wear out surfaces are expose and accessible. After confirmation on the appropriateness of remanufacturing technology, the part will be checked for the cleanliness level via visual inspection. It is identified that the parts are in the cleanliness level 3. Finally, the assessment refines the EoL part recovery decision to remanufacture and recycle. Subsequently, a detailed time cost and environmental impact computation on remanufacturing and recycling will be done for further decision making analysis.

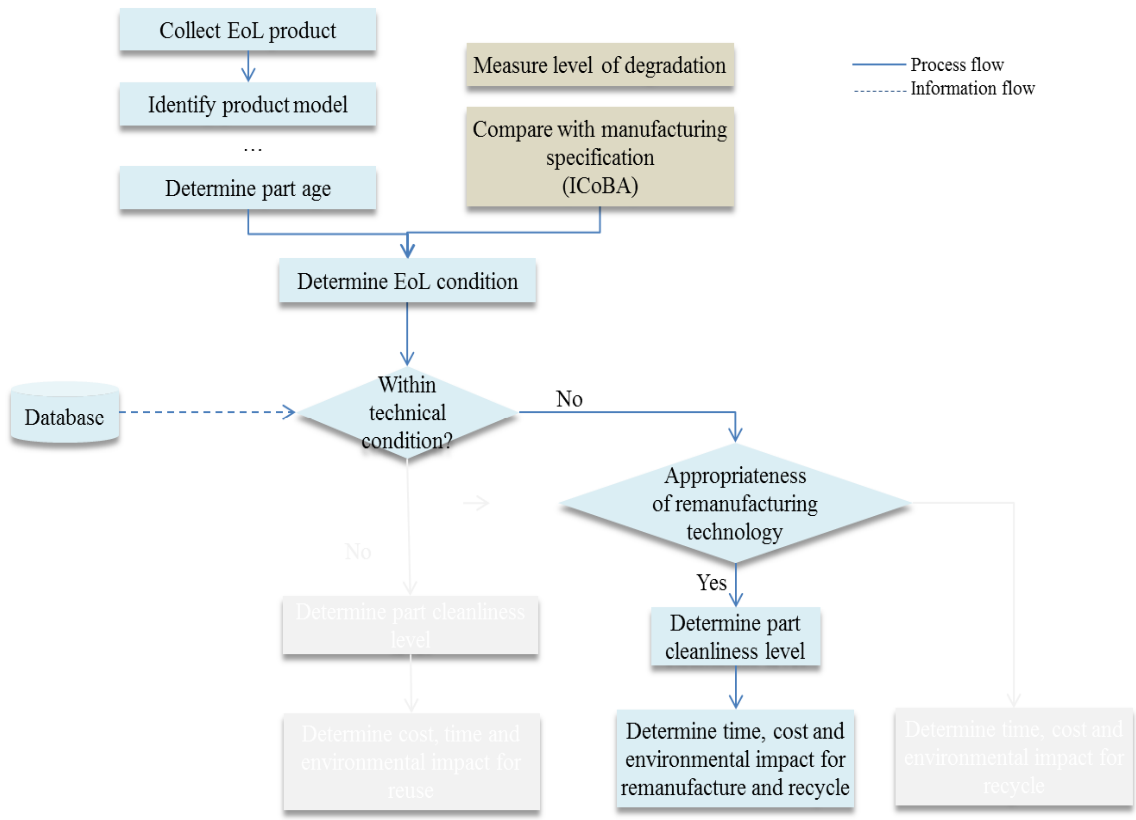


Figure 6-22 Assessment flow for EoL crankshaft

Table 6-24 Example of EoL crankshaft condition

Item number	**Wear-out dimension: Main journal**	**Wear-out dimension: Eccentric journal**	**Life time**	**Remark**
EYY-100E: 11	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
EYY-100E: 12	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
EYY-76E: 2	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
EYY-76E: 3	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
DKK43C: 14	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
EKI120E: 1	< Threshold dimension	< Threshold dimension	> designed life	Minor wear out
etc.		…		…

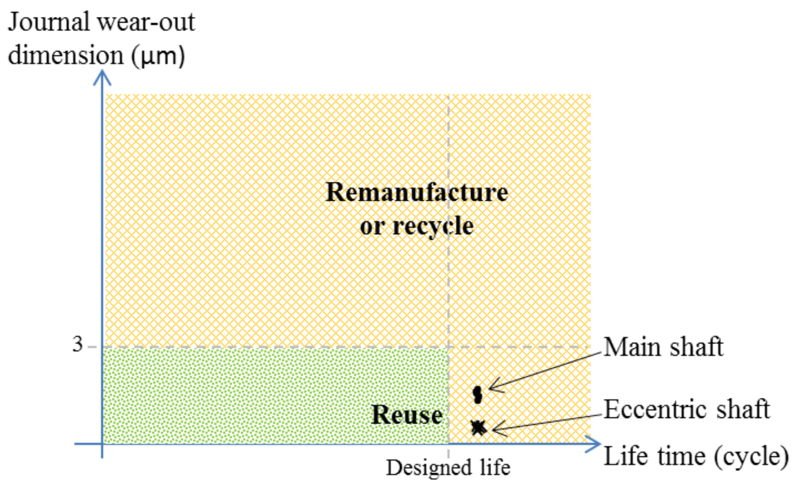


Figure 6-23 Classification of wear out life

6.4.3 Technology and Recovery Flow

In view of the outcome generated from the assessment, manufacturer remains with the recovery option of remanufacturing and recycle. Figure 6-24 illustrates the process flow for remanufacturing crankshaft. Laser cladding is identified as remanufacturing technology to recover crankshaft. It is a processing technique for adding one material onto the targeted surface of another in controlled manner. The cladding thickness can be controlled by designing additive material composition or optimize laser processing parameter. Nickel based powder is fed as the additive material to clad on the surface of the wear out zone. In addition, this technique required minimal heat input, thus it resulted in limited distortion of the substrate and reduces the need for additional corrective machining. Figure 6-25 shows the process flow for crankshaft recycling, which the process steps have no different from the first scenario. Knowing the steps of recovery is particularly important for time, cost and environmental impact quantification in the following analysis.

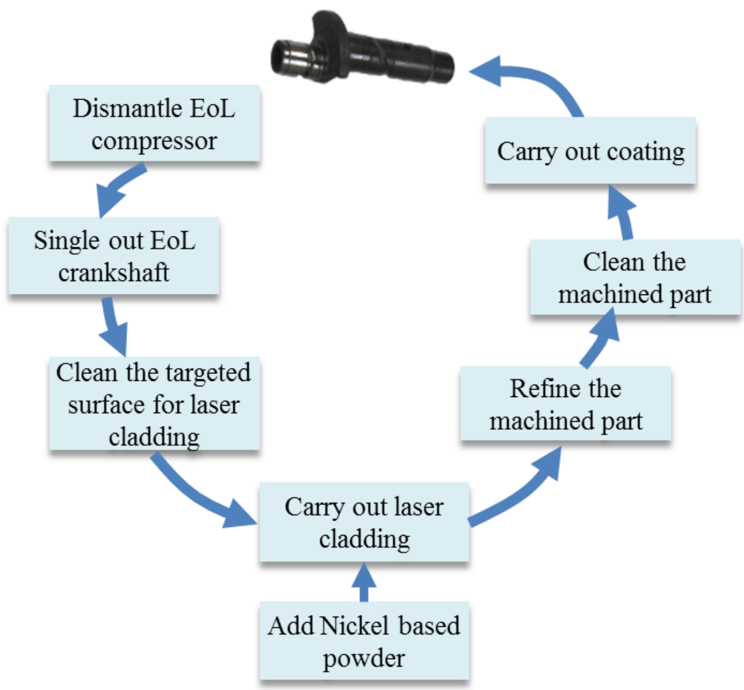


Figure 6-24 Remanufacturing process flow for crankshaft

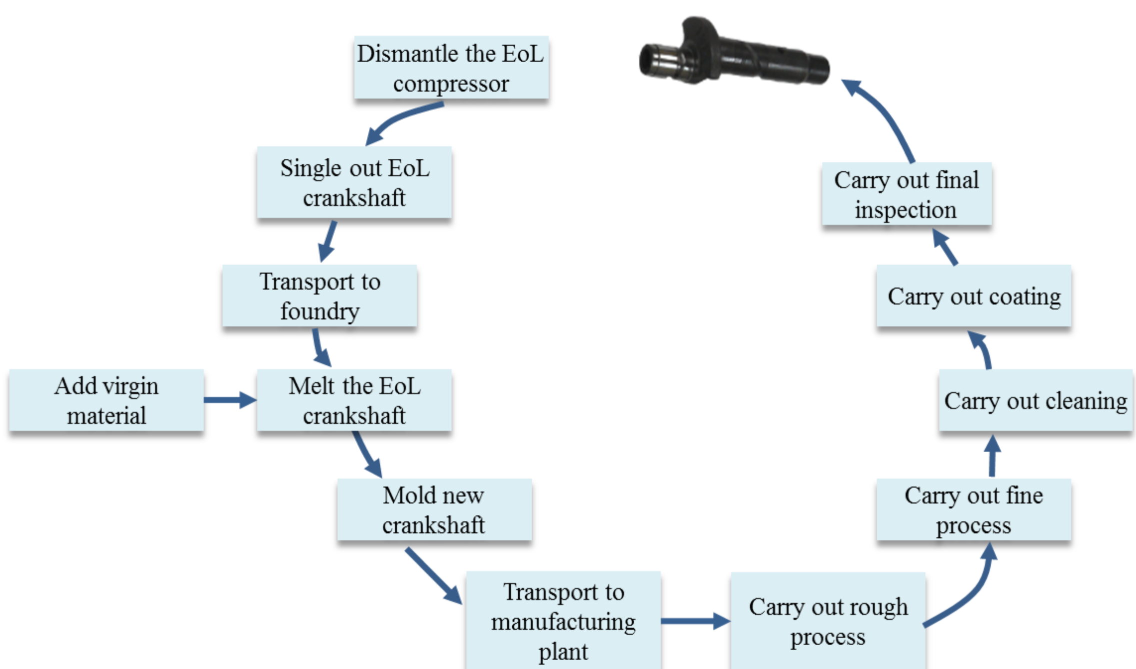


Figure 6-25 Recycling process flow for crankshaft

6.4.4 Model Implementation

The assessment flow has narrowed down the recovery options to part remanufacturing and recycling. Further on, the system shall decide on the best option based on utility score. The following section will quantify the value using particular model for time, cost and environmental impact. Then, the value is translated into utility score in section 6.4.5.

6.4.4.1 Time assessment

Based on the recovery process in Figure 6-24 and Figure 6-25, time spent in recovery activity is assessed. Time consumption for making new crankshaft is calculated using generated formulas from literature search. The measured and calculated data are listed in. Assumption has been made for time assessment in this scenario. The activities in transportation, cleaning, material extraction, melting and shakeout are carried out per batch function in order to achieve production efficiency. Thereby, the time consumes in each activity (per batch) is assumed same as the activity time spent for carrying out one unit. For example, time spent for melting 0.3kg of part weight is equal to time spent in melting 1000kg of raw cast iron (in order to achieve the maximum efficiency). The process step for making new crankshaft is same as the process in scenario 1. Melting, pouring and solidification time are estimated using formulas in Table 6-10. Information as follow is the input data for calculating time spend in particular process activity.

Transportation time, t_{trans} = 30 min/batch

Loading/unloading time, t_{load} = 30 min/batch per load

Cutting time, t_{cut} = 1 min/unit compressor

Dismantling time, t_{dism} = 3 min/unit compressor

Number of recovery part in this scenario, n_{rec_i} = 2 (i = current value)

Rate of cladding, r_{clad} = 600 mm/min

Length of job, l = $2\pi r \times L$ =1570.80 mm

Radius of crankshaft journal, r = 10mm

Length of cladding zone, L = 25mm

Melting time, t_{melt} = 64 min/batch (same furnace capacity and efficiency in Scenario 1)

Pouring time, t_{pour} = 0.12 min/unit

Solidification time, t_{sol} = 0.173 min/unit

Shakeout time, t_{shake} = 1 min/batch

Lathe time, t_{lathe} = 0.255 min/unit

Milling time, t_{mill} = 2.11 min/unit

Table 6-25 Input data and formulas for time consumption

Time components	Measures and formulas	New, t_0	Remanufacturing, t_2	Recycling, t_3
Transport, t_{trans}	$t_{trans} + t_{load}$	-	-	**90 min/batch**
Disassembly, t_{dis}	$\frac{t_{cut}}{unit} + \frac{t_{dism}}{unit}$	-	**3 min/unit**	**2 min/unit**
Cut, $\frac{t_{cut}}{unit}$	$\frac{t_{cut}}{n_{rec\_c}}$	-	0.5min/unit	0.5min/unit
Dismantle, $\frac{t_{dism}}{unit}$	$\frac{t_{dism}}{n_{rec\_c}}$	-	1.5min/unit	1.5min/unit
Inspection, t_{ins}	1 min/unit	-	1 min/unit	-
Clean, t_{clean}	$t_{wash} + t_{dry}$	-	**120min/batch**	-
Wash, t_{wash}	60 min/batch	-	60 min/batch	-
Dry, t_{dry}	60 min/batch	-	60 min/batch	-
Cladding, $\frac{t_{clad}}{unit}$	$r_{clad} \times l$	-	**2.62min/unit**	-
Iron extraction, t_{ext}	1 day	**480 min/batch**	-	**480min/batch**
Casting, t_{cast}	$t_{melt} + t_{pour} + t_{sol} + t_{shake}$	**65.29 min/batch**	-	**65.29 min/batch**
Rough process, $\frac{t_{rough}}{unit}$	$t_{lathe} + t_{mill}$	**2.36 min/unit**	-	**2.36 min/unit**
Fine process, t_{fine}		**101.42 min/batch**	**103 min/unit**	**101.42 min/batch**
Deburring, t_{bur}	0.42 min/unit	0.42 min/unit	-	0.42 min/unit
Refine, t_{refine}	2 min/unit	-	2 min/unit	-
Coat, t_{coat}	1 min/unit	1 min/unit	1 min/unit	1 min/unit
Cure, t_{cure}	60 min/unit	60 min/unit	60 min/unit	60 min/unit
Clean, t_{clean}	40 min/batch	40 min/batch	40 min/batch	40 min/batch
Quality check, t_{check}	0.5 min/unit	**0.5 min/unit**	**0.5 min/unit**	**0.5 min/unit**
Total time		**649.57 min/unit**	**229.12 min/unit**	**741.57min/batch**

6.4.4.2 Cost assessment

Before the recovery cost is assessed, decision maker needs to understand the boundary of material flow. The material flow for making new crankshaft is shown in Figure 6-27 and material flow for closed-loop recycling is shown in Figure 6-27. R_j is the proportion of used material fed back to the manufacturing system. In this case, the new crankshaft consumes 100% of virgin material, which R_0 is 0. However, 60% of the material will be recycled (R_3) and used in making new crankshaft for recycling option, while the remaining material (1-R_3) constitutes of virgin material in order to keep the part quality on par. On the other hand, the leftover EoL part weight (1-R_3) will be formed in the other product system. The cost for each option is termed as c_j, where j = 0 is making new, j = 1 is reuse, j = 2 is remanufacture and j = 3 is recycle. Cost assessment in this scenario includes operation cost, overhead cost, procurement cost and machine depreciation as bolded in Table 6-26. Cost of making new crankshaft is calculated with the input data below using formulas listed in Table 6-26. As for the cost of disassembly, washing, blowing and oven are included in remanufacturing recovery activity, but not in recycling activity. In the cost analysis, it assumes that the EoL compressors are collected when the compressor manufacturer deliver new compressor to refrigerator manufacturer. Thereby, collection cost for end-of-life crankshaft is not applicable in this scenario. The input figures are listed below. Cost of resources may vary for each purchase over 1 year. The latest unit price of Gray cast iron (July 2014), unit cost of nickel based powder (June 2013, information from SIMTech lab), unit price of electricity tariff (July 2014) and unit price of fuel (August 2014) are considered in the calculation.

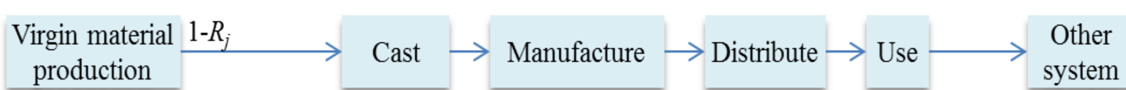


Figure 6-26 Material flow for making new crankshaft

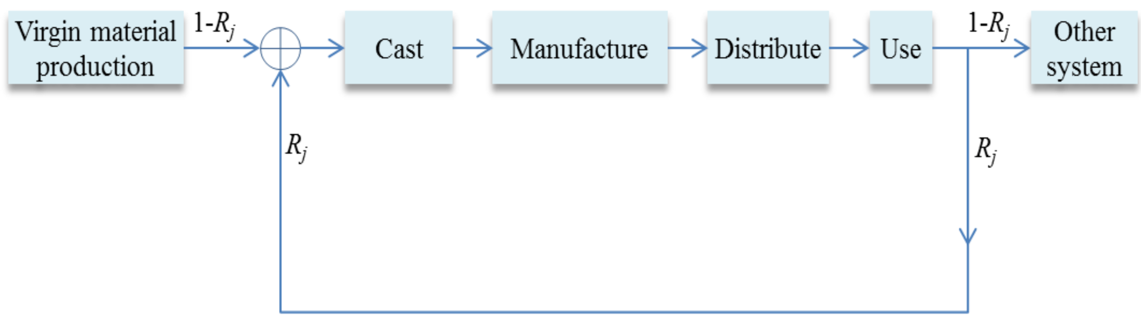


Figure 6-27 Material flows for closed-loop recycling process

Proportion of recycled material used in new part, R_0 = 0

Proportion of recycled material used in new part, R_3 = 0.6

Rating power of induction furnace, p_{fur}= 700 kW

Melting time, t_{melt} = 8 hours

Capacity of furnace, v_{fur} = 1000 kg

Unit weight of crankshaft, w_{crank} = 0.3kg

Unit cost of material, c_{mpu_i} = \$0.12/kg (i = cur)

Defect rate, r_{def}= 0.01

Metal loss in melting, f_1 = 1.07 [155]

Metal loss in pouring, f_2 = 1.04 [155]

Metal loss in frettling, f_3 = 1.04 [155]

Total electricity usage in manufacturing process per unit part, $\sum Elec_{proc\_k}$ = 0.679kWh/unit

Unit cost of electricity, c_{elec_i} = \$0.2345/kWh (i = cur)

Number of manufacturing unit, n_{mfg} = 4,000,000 unit

Cost of refining activity, c_{refine} = \$0.106/unit

Cost of inspection, c_{insp} = \$0.05/unit

Unit cost of nickel, c_{npu} = \$126/kg

Volume of cladding material for crankshaft, v_{crank} = 1.56 X 10^{-7} m^3

Rating power for laser equipment, p_{laser} = 5.6kW

Cladding time, t_{clad} = 0.044 hour

Cost for cutting, c_{cut} = \$0.079/unit

Cost for dismantling, c_{dism} = \$0.237/unit

Cost for assessment, c_{ass} = \$0.25/unit

Cost for washing, c_{wash} = \$0.543/unit

Cost for blowing, c_{blow} = \$0.003/unit

Cost for oven operation, c_{oven} = \$0.088/unit

$Distance_j$, = 40km (j = 0)

$Distance_j$, = 80km (j = 3)

Unit Cost of fuel, c_{fuel_i} = \$0.24/km (i = cur)

Number of unit per truck, n_{truck} = 13200

Table 6-26 Input data and formulas for cost calculation

Cost components	Formulas	Making new, c_0	Remanufacturing, c_2	Recycling, c_3
Operation cost, c_{op_0}	$c_{cast\_0} + c_{mat\_0} + c_{process\_0} + c_{labor\_0}$	**$0.90/unit**	-	-
Casting cost, c_{cast_j}	$\frac{p_{fur} \times t_{melt} \times c_{elec\_i}}{v_{fur}/w_{crank}}$	$0.39/unit	-	$0.39/unit
Material cost, c_{mat_j}	$(1 + r_{def}) \times w_{bpu} \times f_1 \times f_2 \times f_3 \times R_j \times c_{mpu\_i}$	$0.054/unit	-	$0.015/unit
Process cost, $c_{process\_j}$	$\frac{\sum_{k=1}^{n} Elec_{proc\_k} \times c_{elec\_i}}{n_{mfg}}$	$0.16/unit	-	$0.16/unit
Labor cost, c_{labor_j}		$0.298/unit	-	$0.30/unit
Operation cost of remanufacturing, c_{op_2}	$c_{mat\_2} + c_{clad} + c_{dis\_2} + c_{refine} + c_{insp}$	-	**$1.436/unit**	**-**
Material cost, c_{mat_2}	$c_{npu} \times d_n \times v_{crank}$	-	$0.176/unit	**-**
Process cost, c_{clad}	$p_{rate} \times t_{clad} \times c_{elec\_i}$	-	$0.061/unit	**-**
Disassembly cost , c_{dis_j}	$c_{cut} + c_{dism} + c_{ass} + c_{wash} + c_{blow} + c_{oven}$	-	$1.200/unit	$0.37/unit
Operation cost of recycling, c_{op_3}	$c_{cast\_0} + c_{mat\_3} + c_{process\_3} + c_{labor\_3}$	-	-	**$1.235/unit**
Overhead cost, c_{oh_j}		**$0.19/unit**	**$0.095/unit**	**$0.19/unit**
Procurement, c_{proc_j}	$\frac{Disatance_i \times c_{fuel\_i}}{n_{truck}}$	**$0.0007/unit**	-	**$0.0014/unit**
Machine depreciation cost, c_{dep_j}		**$0.241/unit**	**$0.20/unit**	**$0.241/unit**
Total cost		**$1.33/unit**	**$1.73/unit**	**$1.67/unit**

6.4.4.3 Environmental impact assessment

Environmental burden generated from making new and recovering of crankshaft are assessed. The environmental impact caused in the operation system is modeled using SimaPro, focusing on the carbon footprint aspect. Upstream production of material extraction is included in the model. The environmental impact of recycling option is modeled based on the information in Table 6-27. In this scenario, please note that the environmental impact emitted from production of making new product using recycled material and the environmental impact caused in production of making new product using

100% of virgin material are almost same, although 60% of virgin material is replaced by the recycled material. From the modeled results, remanufacturing activities emits nearly half carbon footprint of making new part due to minor re-machine operation.

Table 6-27 Input information for calculating carbon emission

Environmental impact component	**Modeled component**	**Modeled results**
$EI_{op\_j}\|_{j=0}$	(EI. of material extraction + EI. of casting + EI. of rough process + EI. of fine process + EI. of transportation) per unit	0.807kgCO_2eq/unit
$EI_{op\_j}\|_{j=2}$	(EI. of disassembly + EI. of re-machine + EI. of refining) per unit	0.495kgCO_2eq/unit
$Ei_{op\_j}\|_{j=3}$	(EI. of disassembly + (1-R_1) EI. of material extraction + EI. of casting + EI. of rough process + EI. of fine process + EI. of transportation) per unit	0.809kgCO_2eq/unit

6.4.5 Decision Analysis

After going through part assessment, the recovery options remain remanufacturing or part recycling. Without detailed study, decision maker would judge the decision based on relative perception. The judgment is inconsistent with illusory basis. However, the research method leads manufacturer makes an inform decision. Model implementation in previous section estimates the time, cost and carbon emission of manufacturing new part and EoL part recovery. This is followed by converting the estimated values into utility value from 0 (worst) to 1 (best). Therefore, the maximum (worst) and minimum (best) values are required to set as the threshold value. The threshold setting will be explained in the subsequent paragraphs.

The similar key parameters mentioned in scenario 1 (Table 6-13) are identified as the determinant for the maximum and minimum range. Choosing the parameter values that generate minimum outcome with reuse option will give the minimum threshold is this scenario. On the contrary, parameter values that generate maximum outcome with recycling option set the maximum threshold, as listed in Table 6-28. After generating the threshold values, time spent in manufacturing new part is chosen as the mid value ($x_{0.5}$), which set as the reference value for equal chance of saving 528.37 minute/unit or spending extra 136.71 minute/unit. This approach has incorporated the manual way of mid value seeking through asking the decision maker's preference limit. With the assigned mid value, normalized exponential constant (R_{time}) and risk tolerance (ρ_{time}) for the particular time range can be identified. Lastly, the time utility function curve is plotted with the input information in Figure 6-28. Any recovery time below 121.20 will be assigned as utility of 1 and recovery time above 786.28 is quantified as zero utility. The time utility function curve presents the risk aversion.

Table 6-28 Threshold estimation for time

Threshold for time	Calculation	Value
$t_{min} = t_1\|_{n_{rec}=20}$		121.20 min/unit
t_1	123 min/batch	
$t_{max} = t_3\|_{n_{rec}=1,\,\text{Delay}}$		786.28min/unit
$t_3\|_{n_{rec}=1}$	743.57 min/unit	
Delay	7% of t_0	

Table 6-29 Input data for generating time utility function curve

Input	**Value**
Maximum time, at u(t_{max}) = 0	786.28 min/unit
Minimum time, at u(t_{min}) = 1	121.20 min/unit
Midvalue, $x_{0.5} = t_0$	649.57 min/unit
R_{time}	0.324
Risk tolerance, ρ_{time}	215

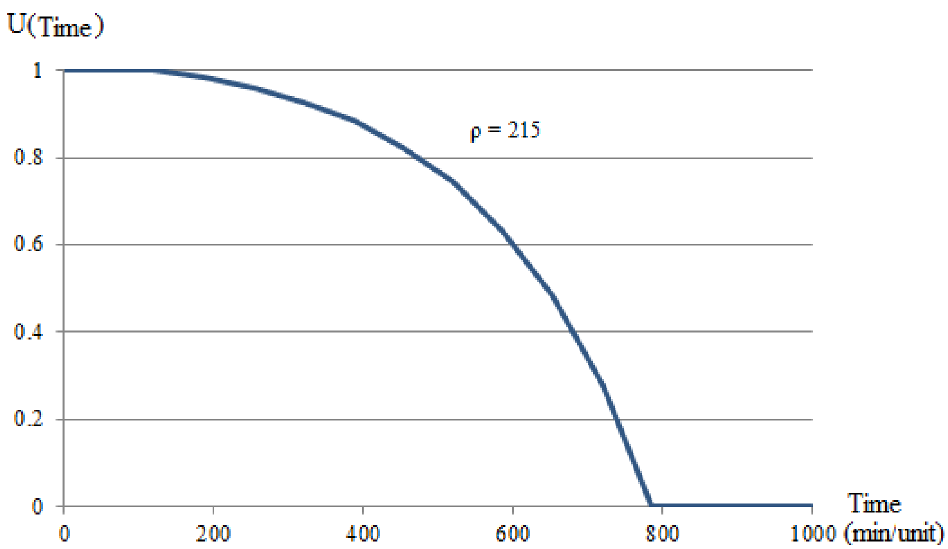


Figure 6-28 Utility function curve for time

Likewise, several key variables that affect the minimum and maximum cost range are identified in Table 6-30. From the cost analysis in previous section, cost of remanufacturing is proven as the highest cost for crankshaft recovery. As such, remanufacturing cost is used as the reference for maximum cost. Nickel based powder used in laser cladding is uncommon in historic data, special request for quotation is needed. Thereby, the minimum and maximum values are referring to the decreasing and increasing percentage of nickel price chart for 4 years period from January 2010 to July 2014 [156]. The unit cost of electricity is referring to Singapore electricity tariff for High Tension Large (HRL) supplies in between January 2010 to July 2014 [157]. And the cost of fuel refers to Singapore petro fluctuation chart from July 2011 to August 2014 [158]. The length of cladding is another related cost indicator for remanufacturing recovery option. As longer cladding length requires more volume of nickel based powder for cladding. The worst case of clad the whole crankshaft rod is considered in this scenario. Number of part for recovery (n_{rec}) is also identified as key variable because it largely influences on the total recovery cost, especially cost of disassembly. With the minimum values in reuse option, the least time spent is set as minimum threshold. On the opposite, maximum values apply in remanufacturing option set the maximum threshold for cost, which all the values are listed in Table 6-31. The cost of making new crankshaft is assigned as mid value for the exponential curve function, which represents the equal probability of preference over saving $2.34/unit or losing $1.97/unit. Then, the normalized exponential constant (R_{cost}) and risk tolerance (ρ_{cost}) for the particular cost range are identified using Equation (6-2). Finally, the cost utility function curve is plotted (in Figure 6-29) with the input information in Table 6-32. Any recovery cost below 0.96 will be assigned as utility of 1 and recovery cost above 3.30 is quantified as zero utility. The cost utility function curve shows risk seeking trend.

Table 6-30 Key variables for determining cost threshold

Key variable	**Unit**	**Minimum value, *i*=min**	**Current value, *i*=cur**	**Maximum value, *i*=max**
Cost of raw material, c_{npu_i}	\$/kg	63	126	189
Cost of electricity, c_{elec_i}	\$/kwh	0.2076	0.2345	0.2721
Cost of fuel, c_{fuel_i}	\$/km	0.2250	0.2503	0.2548
Length for cladding, l_{clad}	mm	25	25	120
Number of recovery part, n_{rec_i}	unit	20	2	1

Table 6-31 Threshold values for cost

Threshold for cost	**Calculation**	**Value**
c_{min}	$c_1\|_{n_{rec}=20,\ i=\text{min}}$	\$0.96/unit
c_{max}	$c_2\|_{n_{rec}=1,\ i=\text{max}}$	\$3.30/unit

Table 6-32 Input data for generating cost utility function curve

Input	**Value**
Maximum cost, at $u(c_{max}) = 0$	\$3.30/unit
Minimum cost, at $u(c_{min}) = 1$	\$0.96/unit
Midvalue, $x_{0.5} = c_0$	\$1.33/unit
R_{cost}	-0.236
Risk tolerance, ρ_{cost}	-0.553

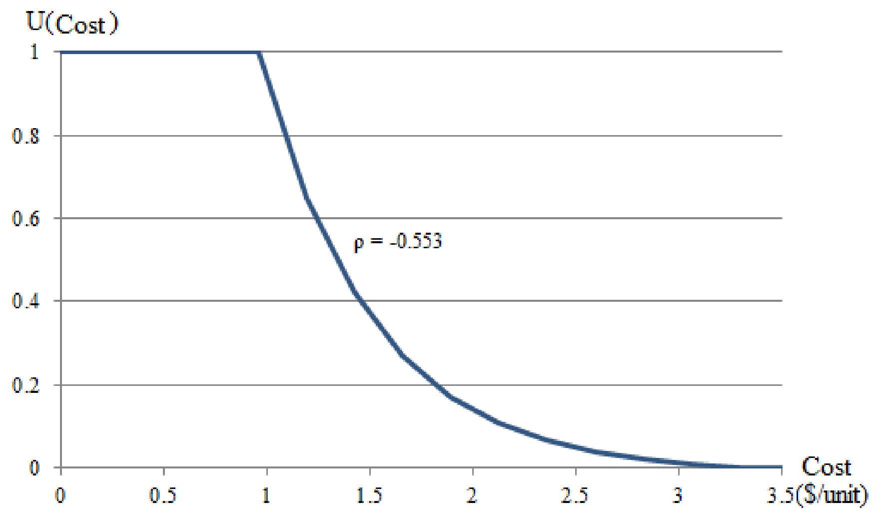


Figure 6-29 Utility function curve for cost

Determination of threshold value for environmental impact is rather straight forward. Carbon emission is identified as the environmental impact indicator, which the least emission caused in reuse option and the most carbon emission caused in part recycling. However, according to the survey, the overall current carbon emission from business as usual (BAU) case is unpromising. As such, translating the carbon emission of country level to production line level, making new part shall be the maximum emission limit. In other words, this approach preempts the regulation of carbon reduction. In accordance to the environmental policy set by individual government, the values are applied as the benchmark. As mentioned in Chapter 3, Singapore government has pledge on yearly reduction of carbon emission by 3.6%.Thereby, a reduction of 3.6% from BAU crankshaft production is set as the mid value ($x_{0.5}$), which serve reference for equal probability on saving 0.644kgCO_2eq or losses 0.029kgCO_2eq. Subsequently, the normalized exponential constant (R_{EI}) and risk tolerance (ρ_{EI}) for the particular carbon emission range are identified using Equation (6-2). Finally, the utility function curve for environmental impact using carbon emission as indicator is plotted in Figure 6-30.

Carbon emission below 0.134 has utility of 1 and above 0.807 is zero utility. The carbon emission utility function curve shows risk averse trend.

Table 6-33 Threshold values for carbon emission

Threshold for carbon emission	**Value**
$EI_{min} = EI_1$	0.134kgCO_2eq/unit
$EI_{max} = EI_0$	0.807kgCO_2eq/unit

Table 6-34 Input data for generating carbon emission utility function curve

Input	**Value**
Maximum carbon emission, at u(EI_{max}) = 0	0.807kgCO_2eq/unit
Minimum carbon emission, at u(EI_{min}) = 1	0.134kgCO_2eq/unit
Midvalue, $x_{0.5} = (1\text{-}0.036)*EI_0$	0.778kgCO_2eq/unit
R_{EI}	0.058
Risk tolerance, ρ_{EI}	0.039

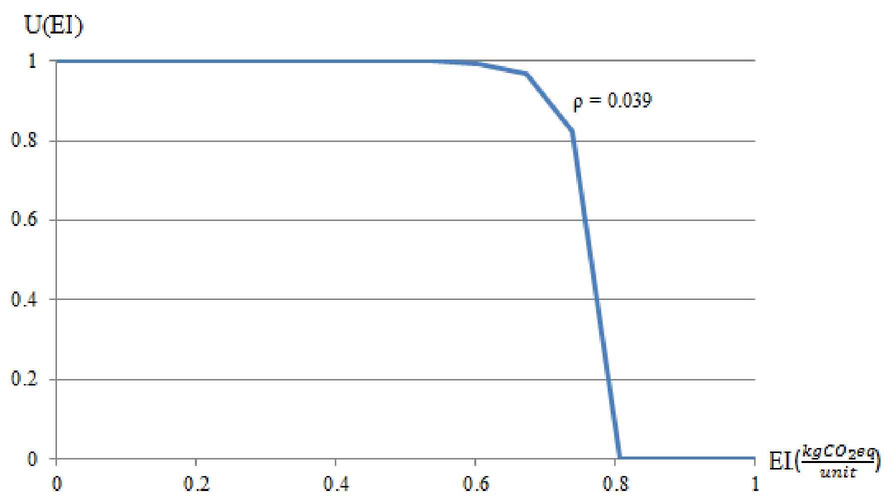


Figure 6-30 Utility function curve for carbon emission

Gathering all the utility plots, carbon emission shows the highest degree of risk attitude. This is followed by cost and the lowest degree of risk is time. The measuring unit for carbon emission and cost is about the same range, thereby comparing the values of ρ give the relative importance for the weight. Further analysis is done for computing the gradient of curve due to the different measuring scale between time and cost. The step is to quantify the significance of one attribute over another. For instance, the higher the gradient is, more heighten the risk attitude. Results in Table 6-35 shows the gradient of the plots, where cost has higher gradient than time. The information then can be used as reference for pairwise comparison.

Table 6-35 Gradient calculations for time and cost utility function

Attributes	**Time**		**Cost**	
	U(Time)	Gradient	U(Cost)	Grad ient
	1		1	
	0.982699	0.000260	0.649538	1.494713
	0.959141	0.000354	0.420126	0.978441
	0.927066	0.000482	0.269952	0.640489
	0.883394	0.000657	0.171648	0.419265
	0.823931	0.000894	0.107298	0.274451
	0.742967	0.001217	0.065174	0.179656
	0.632729	0.001658	0.037600	0.117603
	0.482632	0.002257	0.019550	0.076983
	0.278263	0.003073	0.007735	0.050393
	0		0	
Average		**0.00121**		**0.47022**

According to Saaty's intensity of importance scale (in Appendix A1), environmental impact is assigned as 3 times more important than cost and 9 times more important than time. Besides, the cost is 5 times more important than time. Pairwise comparison is performed using the scale, as shown in Table 6-36

.

Table 6-36 Input for pairwise comparison

	Time, a_1	**Cost, a_2**	**Environmental impact, a_3**
Time, a_1	1	1/5	1/9
Cost, a_2	5	1	1/3
Environmental impact, a_3	9	3	1

Then, an ***A***-matrix is generated based on the comparison table.

$$\boldsymbol{A} = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{9} \\ 5 & 1 & \frac{1}{3} \\ 9 & 3 & 1 \end{bmatrix}$$

Rewrite the matrix into equations such that determinant of the coefficient matrix is zero.

$$Det(A - \lambda I) \begin{vmatrix} 1-\lambda & \frac{1}{5} & \frac{1}{9} \\ 5 & 1-\lambda & \frac{1}{3} \\ 9 & 3 & 1-\lambda \end{vmatrix} = 0$$

$$(A - \lambda I)w = 0 \rightarrow \quad (1-\lambda)w_1 + \frac{1}{5}w_2 + \frac{1}{9}w_3 = 0$$

$$5w_1 + (1-\lambda)w_2 + \frac{1}{3}w_3 = 0$$

$$9w_1 + 3w_2 + (1-\lambda)w_3 = 0$$

Solving the above equations above give weightage for the three attributes w_1 = 0.064; w_2 = 0.267; w_3 = 0.669. Finally, the total utility *u(j)* can be computed using Equation (3-3). The decision tree diagram is illustrated in Figure 6-31, which it clearly shows that remanufacturing option obtains the higher utility value than making new and recycling. Thereby, the decision shall be made based on the higher utility value.

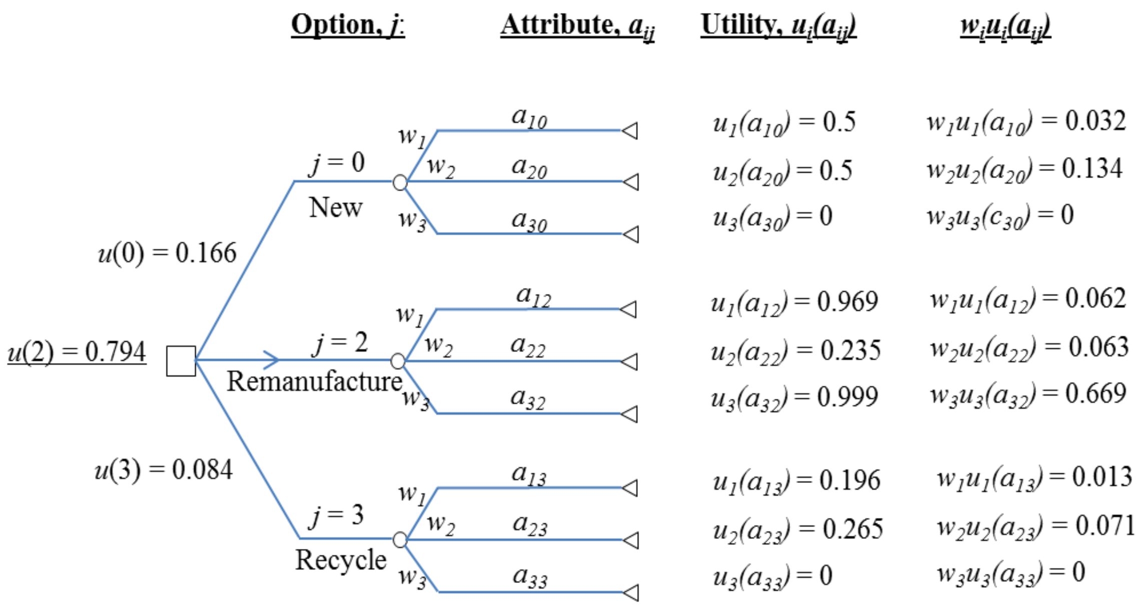


Figure 6-31 Decision tree for crankshaft recovery

6.4.6 Remarks of the Second Scenario

The above scenario has further justified the developed assessment framework and model is useful for supporting product recovery decision making process. The selection of threshold value is critical for determining the recovery potential of the EoL parts. Therefore, manufacturers have to include as comprehensive component as possible in establishing the right threshold in order to accommodate the company's interest.

The time analysis adds a new dimension on the dynamic of production. It informs the knowledge needed for resource planning for future study. In addition, the cost profile generated at the end of the calculations can be used further analysis to detect any possibility of improvement. Cost exercise would increase the EoL part recovery from time, economic and environmental point of view in future. Also, the analysis reveals that including environmental aspect into the assessment strengthens the superiority of remanufacturing. Overall, the outcome is confirmed to be useful to provide insights in decision making process.

The recovery value of crankshaft is summarized in Table 6-37. From the analysis, remanufacturing recovery saves on time and environmental impact, however disadvantage in cost. Looking at the values, decision maker might judge the circumstances based on apparent comparison on two gains out of three attributes. However, the different measuring units are incomparable. Manufacturer could not justify decently on the level of losses in cost against the gains in time and environmental impact. Thereby, utility value plays a key role in standardizing the calculated values across all attributes with different measure. It quantifies the computed values in the range of 0 to 1. Lastly, allocation of weights implies the manufacturer interest on particular performance. Comparing the utility of remanufacturing to making new, overall gain in remanufacturing option is undeniable.

Likewise, when recycling option is compared with making new crankshaft, there is zero recovery value. Although 60% of virgin material can be replaced by recycled material, the disassembly cost has outweighed the cheap raw material cost. This study enlightens manufacturer to further improve in product design for ease of disassembly or enhance the disassembly process. Overall, remanufacturing is concluded as the best recovery option.

Table 6-37 Summary of crankshaft recovery value

	Time, a_{1j} (min/unit)	$u_1(a_{1j})$	w_1	**Cost, a_{2j} ($/unit)**	$u_2(a_{2j})$	w_2	**EI, a_{3j} ($kgCO_2eq$/unit)**	$u_3(a_{3j})$	w_3	**Total**, u(j) = $\sum_{i=1}^{3} w_i \cdot u_i(a_{ij})$
New, *j*=0	649.57	0.5	0.064	1.34	0.5	0.267	0.807	0	0.669	0.166
Remanufacture, *j*=2	229.12	0.969	0.064	1.73	0.235	0.267	0.495	0.999	0.669	0.794
Δ (2 – 0)	**420.45**			**(0.39)**			**0.312**			**0.628**
Recycle, *j*=3	741.57	0.20	0.064	1.67	0.265	0.267	0.809	0	0.669	0.084
Δ (3 – 0)	**(92)**			**(0.33)**			**(0.002)**			**(0.082)**

6.5 Summary

The case study has gone through the research framework and two scenarios are presented. EoL parts that are returned from production reject and end of use specify the two scenarios. Then, the two scenarios illustrated quantification of EoL part condition using ICoBA. This is followed by characterization based on part recovery option. Moreover, threshold value for each attribute is determined and information of making new part is used as the reference point in MAUT decision analysis. Thereby, the estimated outcomes are judged reasonably with reference to the standard value. Finally, total utility value for all recovery options is compared and the highest value is chosen as the optimal recovery solution. Ultimately, the two scenarios verify the developed model is useful to support decision making for part recovery.

CHAPTER 7

Conclusion and Future Work

This chapter summarizes the important findings from the research and highlights the contributions of the study. It is followed by briefing on the limitations of work and identifying new opportunities for future research.

7.1 Research Summary

EoL product recovery is deemed as one of the solutions towards sustainable development. However, the implementation of EoL product recovery system has certain challenges to companies. Decision makers must know the purpose of product recovery (*What*) and define the right time to take action (*When*). Managers shall identify the right expert to solve the problem (*Who*). Engineers and technicians ought to know the root cause of the problems (*Why*) and the detail steps to solve the problems (*How*).

In order to fill the research gaps and meet the objective of this thesis, EoL product recovery framework is proposed to close the information loop. Hence, an overall product recovery framework that depicts the whole process for management reference is proposed in the thesis. The overall framework also comes with assessment flow to assist engineers and technicians to carry out recovery activities. Accordingly, models and decision tools are developed to support decision making in product recovery. The goal of the solution is to minimize time, cost and environmental impact. Using the MAUT method, the higher utility value indicates optimal recovery solution.

With the available information, ICoBA is applied to identify and quantify EoL product condition with reference to the manufacturing data. Also, ICoBA is applied in decision analysis using the manufacturing data as reference. In addition, modeling of threshold value that set the acceptance boundary is developed. Eventually, the quantified (calculated) values are converted into universal scale from 0 to 1. During the threshold value determination for environmental impact, environmental target such as carbon reduction pledged by the government has been included in the model so that the result would always preempt for the environmental regulations. With the readily available manufacturing data, EoL product condition can be accurately predicted and the choice for recovery options based on the product condition is distinguishable. Through MAUT method, various scale and unit of measurements are converted into universal unit so that fair comparison can be carried out to identify the optimal recovery outcome.

The research method for identifying product recovery option was demonstrated on a case study with two scenarios. In the first scenario, cylinder block of refrigerator compressor is used to demonstrate the considerations in decision making for part recovery. The assessment flow in EoL product recovery framework guides the decision maker filter out the choices of recovery option. During the assessment, the source of part return is first identified, followed by indication of part defect. Owing to the unavailability of right technology for the particular part structure, the part is decided for recycling as the recovery option. Overall, the recovery value (also referred as utility value) for recycling has performed slightly better than manufacture a new product.

In the second scenario, crankshaft of refrigerator compressor under study has reached the end of its life. After the part condition assessment, two possible recovery solutions are identified: remanufacture and recycle. Actual data from production is fed into the cost and environmental models, while theoretical cum public data are supplied to the time model to compute the recovery value. The analyzed results show that remanufacture fetched the highest utility value. Overall, remanufacture is 63% better than making new and 71% better than recycling for crankshaft.

From the case study, it justified the proposed method is effective in providing recovery solution methodically. It also proves that the method is generic for wide range of scenarios and applications, without compromising the details that enable comprehensive evaluation on EoL recovery options.

7.2 Research Contributions

The challenges discussed in Section 1.3 and research questions identified in Section 1.4 are addressed in order to achieve the objective of this thesis. Thus, following points highlight the contributions of this work.

i. The research framework proposed in this thesis realized the EoL product condition quantitatively, which the quantitative values further support decision making analysis for EoL product recovery. The framework incorporated the rich manufacturing data as the reference to determine EoL part condition. Particularly, the framework guides engineers and technicians recognize the EoL part condition and quantify the condition into measurable unit regardless of background knowledge and skill. Quantification of EoL part is important as the quantified figures justify the benefits of recovered product and inform the decision maker or consumer in tangible form. On top of that, it helps in comprehending the decision maker in management for business planning.

ii. Alongside with the systematic process, determination of threshold value is proposed to set the acceptance boundary for particular attribute. This method standardizes the condition for all random EoL product conditions. Moreover, the particulars for all attributes are modeled to consider for the detail necessary and accuracy. Consequently, it generates an accurate and consistent result.

iii. The decision analysis method developed in this thesis brought up a new way of decision making in product recovery rather than ranking. The MAUT analysis outcome gives an insight on the significance of particular criteria. For instance, the generated curves indicated the significance of particular criterion. Subsequently, such information can be used as the input for pairwise comparison rather than subjective input based on decision maker's preference. More importantly, the method allows integration of multi-scale and multi-criteria performance across wide variety of product to generate a rational solution.

7.3 Limitations and Direction for Future Research

A broad consideration has been made to cover all the important aspects in the study, however there are still limitations yet to be improved. The limitations mention will be the opportunities for future development and improvement in the area of research.

- Going through the study, the condition assessment is only considered for single part at a time. It might be time consuming and inefficient for the product with hundreds of part. However in practical, different models and specifications of product may be assessed and recovered using the same system. Thereby, the possibility of multiple parts from different models of product going through the same assessment system shall be considered in the scope for future study.

- The outcome from the proposed research method has no influence on product design, which is the downside for manufacturer who has product design team. Lack of such function impotent the company response proactively upfront before the product is manufactured. However, high product recovery efficiency and productivity is achievable by closing the information loop between product design and EoL management. As such, the study in prospect should anticipate product design information to have better impact on product recovery improvement.
- The existing research framework has manually linked the input information based on the requirement in decision making process. However, the framework would be getting unorganized and erroneous if it has to handle a more complicated situation. Hence, data management or data accessing system could be potentially useful in improving process efficiency and accuracy.
- Lastly, development of software program for model implementation would be further simplify the decision making process.

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Appendices

A1: Saaty's Intensity of Importance Scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

A2: Random Indices

Size of matrix	Random Index (RI)
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56
14	1.57
15	1.58

B1: Environmental Impact Models (Simapro) - Block

BLOCK

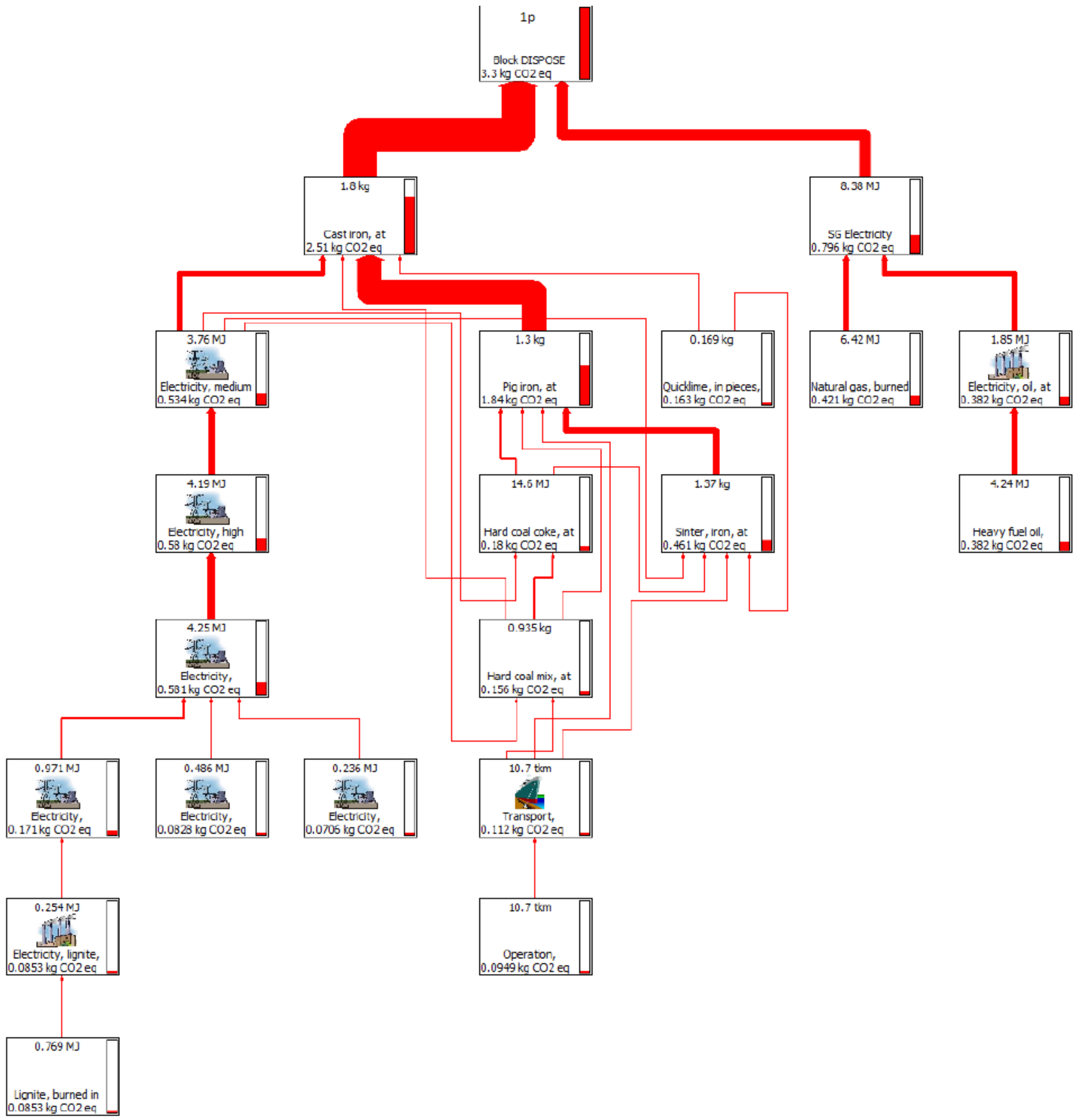
kg CO_2 Equivalent

Calculation:	Compare
Results:	Impact assessment
Product 1:	1 p Block REUSE (of project Panacomp)
Product 2:	1 p Block REMAN (of project Panacomp)
Product 3:	1 p Block RECYCLE (of project Panacomp)
Product 4:	1 p Block DISPOSE (of project Panacomp)
Method:	ReCiPe Midpoint (E) V1.06 / World ReCiPe E
Indicator:	Characterisation
Unit:	%
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Impact category	Unit	Block REUSE	Block REMAN	Block RECYCLE	Block DISPOSE
Climate change	kg CO2 eq	0.133710647	0.495261865	0.796658026	3.304473862
Ozone depletion	kg CFC-11 eq	1.95267E-08	7.22434E-08	1.16531E-07	2.12351E-07
Human toxicity	kg 1,4-DB eq	0.209302561	0.789808241	1.249514903	52.46658811
Photochemical oxidant formation	kg NMVOC	0.000459113	0.001700742	0.002736549	0.011979862
Particulate matter formation	kg PM10 eq	0.000190181	0.000706277	0.001133335	0.010706883
Ionising radiation	kg U235 eq	0.00150469	0.005713475	0.008990098	0.49251114
Terrestrial acidification	kg SO2 eq	0.000710878	0.002632247	0.004236169	0.014859873
Freshwater eutrophication	kg P eq	2.20764E-06	8.62744E-06	1.3183E-05	0.001517912
Marine eutrophication	kg N eq	2.12752E-05	7.88544E-05	0.000126773	0.000692754
Terrestrial ecotoxicity	kg 1,4-DB eq	0.000109595	0.000408539	0.000653024	0.011162353
Freshwater ecotoxicity	kg 1,4-DB eq	0.000119252	0.000455214	0.000711508	0.046826461
Marine ecotoxicity	kg 1,4-DB eq	0.278067935	1.047948187	1.657693164	65.32261212
Agricultural land occupation	m2a	5.55369E-05	0.000227718	0.000331637	0.072887499
Urban land occupation	m2a	0.000136309	0.000511407	0.000814254	0.024563968
Natural land transformation	m2	4.99081E-05	0.000184679	0.000297798	0.000650545
Water depletion	m3	0.000360989	0.001341356	0.002151973	0.022756211
Metal depletion	kg Fe eq	0.000573408	0.002648498	0.003420915	1.718671541
Fossil depletion	kg oil eq	0.051348145	0.190182224	0.306352833	1.235648266

BLOCK

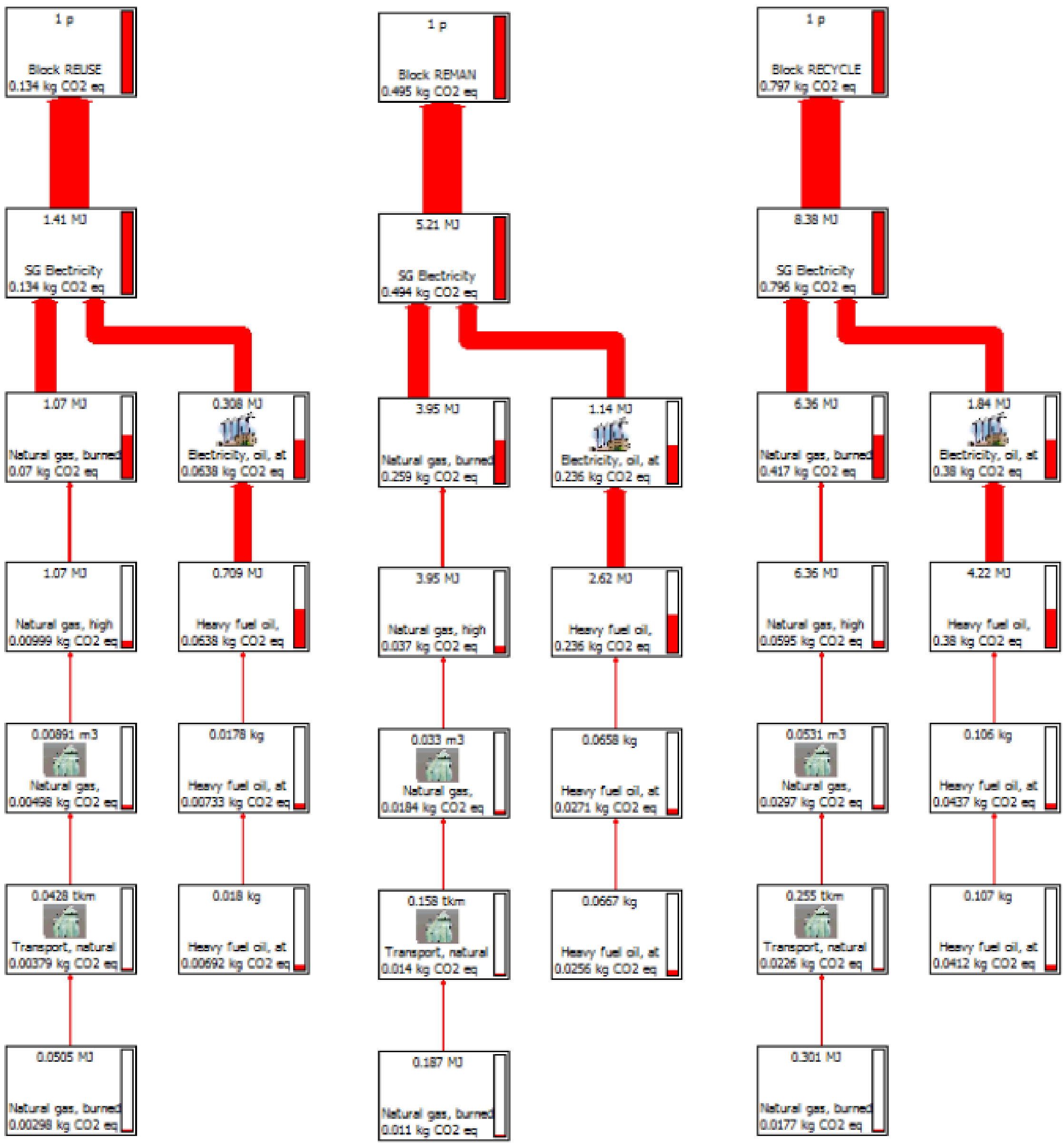
Process Network (Dispose) – 5% cutoff



B1: Environmental Impact Models (Simapro) - Block

BLOCK

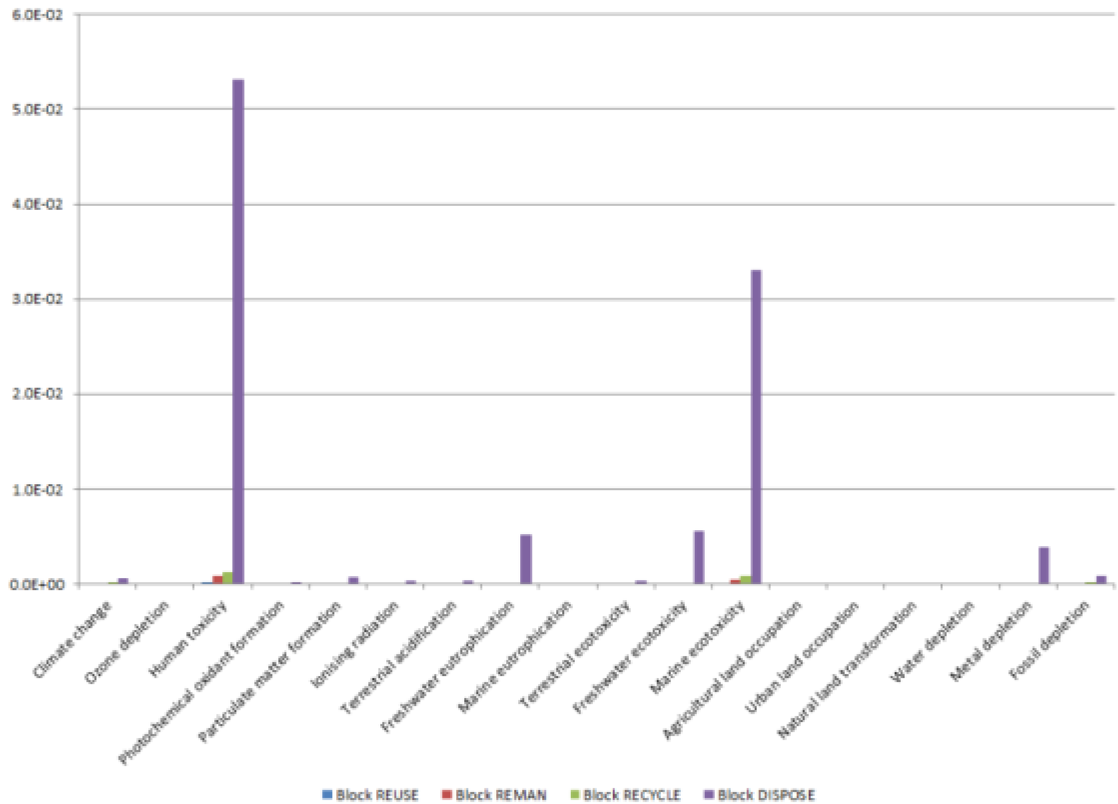
Process Network (Reuse, Remanufacture, Recycle) – 2% cutoff



B1: Environmental Impact Models (Simapro) - Block

BLOCK

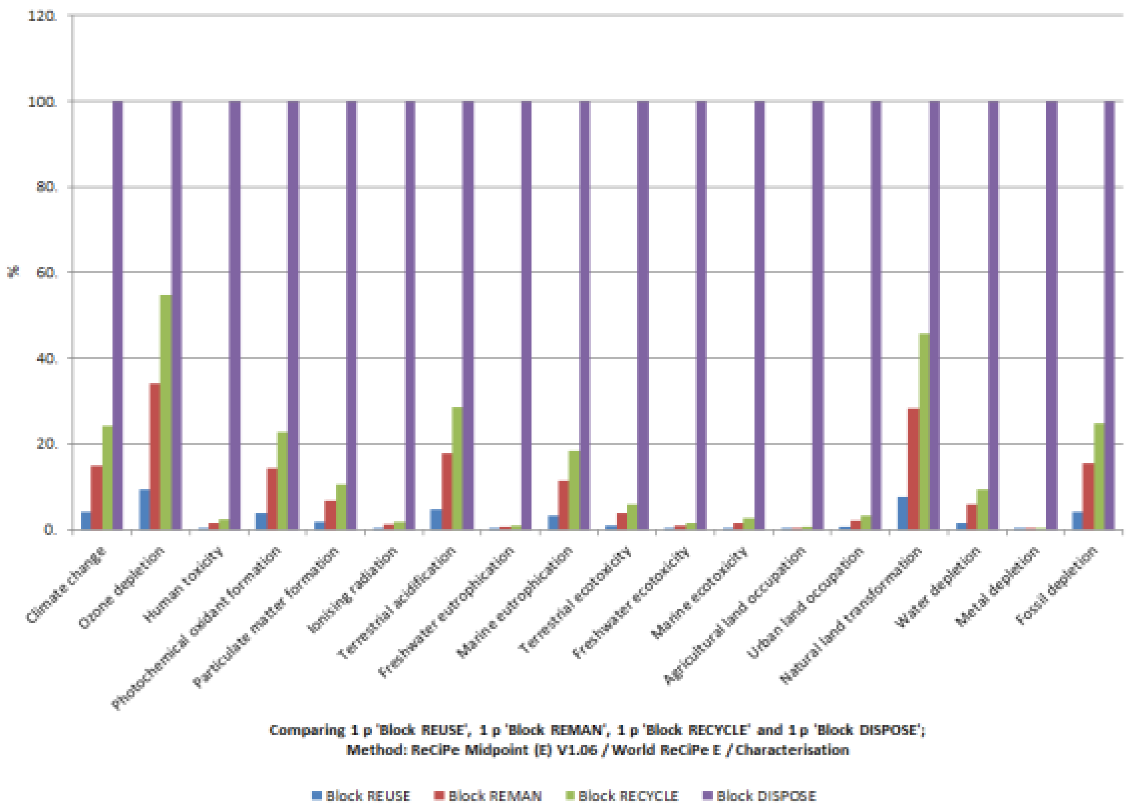
Normalised Chart



B1: Environmental Impact Models (Simapro) - Block

BLOCK

Characterised Chart



B2: Environmental Impact Models (Simapro) - Crankshaft

CRANKSHAFT

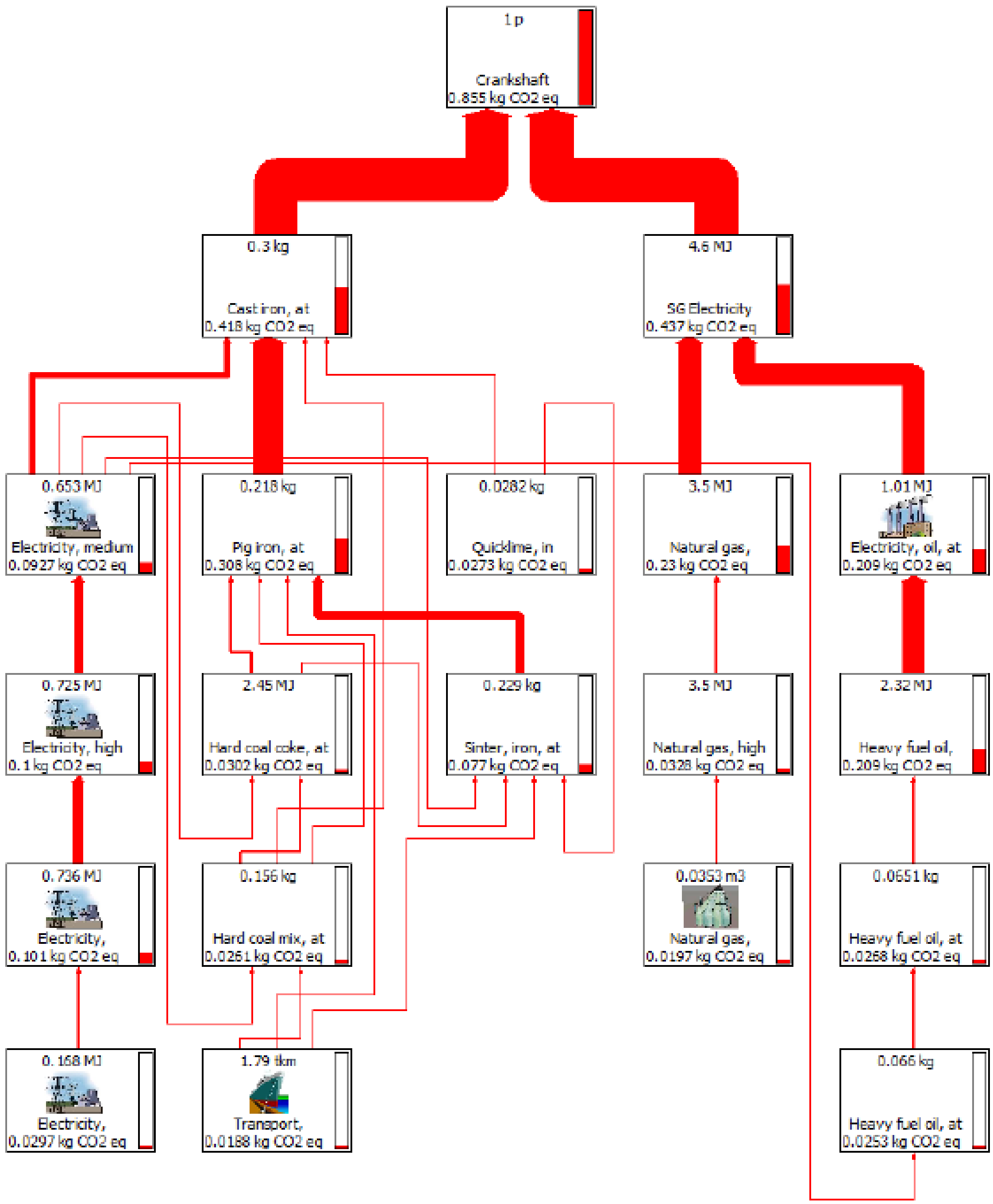
kg CO_2 Equivalent

Calculation:	Compare
Results:	Impact assessment
Product 1:	1 p Crankshaft REUSE (of project Panacomp)
Product 2:	1 p Crankshaft REMAN (of project Panacomp)
Product 3:	1 p Crankshaft RECYCLE (of project Panacomp)
Product 4:	1 p Crankshaft DISPOSE (of project Panacomp)
Method:	ReCiPe Midpoint (E) V1.06 / World ReCiPe E
Indicator:	Characterisation
Unit:	%
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Impact category	Unit	Crankshaft REUSE	Crankshaft REMAN	Crankshaft RECYCLE	Crankshaft DISPOSE
Climate change	kg CO2 eq	0.133710647	0.546751169	0.43740024	0.855369546
Ozone depletion	kg CFC-11 eq	1.95267E-08	7.97418E-08	6.38945E-08	7.98646E-08
Human toxicity	kg 1,4-DB eq	0.209302561	0.874058437	0.684912327	9.221091194
Photochemical oxidant formation	kg NMVOC	0.000459113	0.001877586	0.001501976	0.003042528
Particulate matter formation	kg PM10 eq	0.000190181	0.000779976	0.000622151	0.002217742
Ionising radiation	kg U235 eq	0.00150469	0.00632806	0.00492454	0.085511381
Terrestrial acidification	kg SO2 eq	0.000710878	0.002905782	0.002325523	0.00409614
Freshwater eutrophication	kg P eq	2.20764E-06	9.59056E-06	7.22452E-06	0.000258013
Marine eutrophication	kg N eq	2.12752E-05	8.70599E-05	6.95977E-05	0.000163928
Terrestrial ecotoxicity	kg 1,4-DB eq	0.000109595	0.000451395	0.000358516	0.002110071
Freshwater ecotoxicity	kg 1,4-DB eq	0.000119252	0.000504524	0.000390197	0.008076023
Marine ecotoxicity	kg 1,4-DB eq	0.278067935	1.159540211	0.909716756	11.52053658
Agricultural land occupation	m2a	5.55369E-05	0.000254627	0.000181744	0.012274388
Urban land occupation	m2a	0.000136309	0.000565534	0.000446094	0.00440438
Natural land transformation	m2	4.99081E-05	0.000203853	0.000163303	0.000222094
Water depletion	m3	0.000360989	0.001481434	0.001180995	0.004615034
Metal depletion	kg Fe eq	0.000573408	0.003000931	0.001876172	0.287751277
Fossil depletion	kg oil eq	0.051348145	0.209952763	0.168011633	0.322894205

CRANKSHAFT

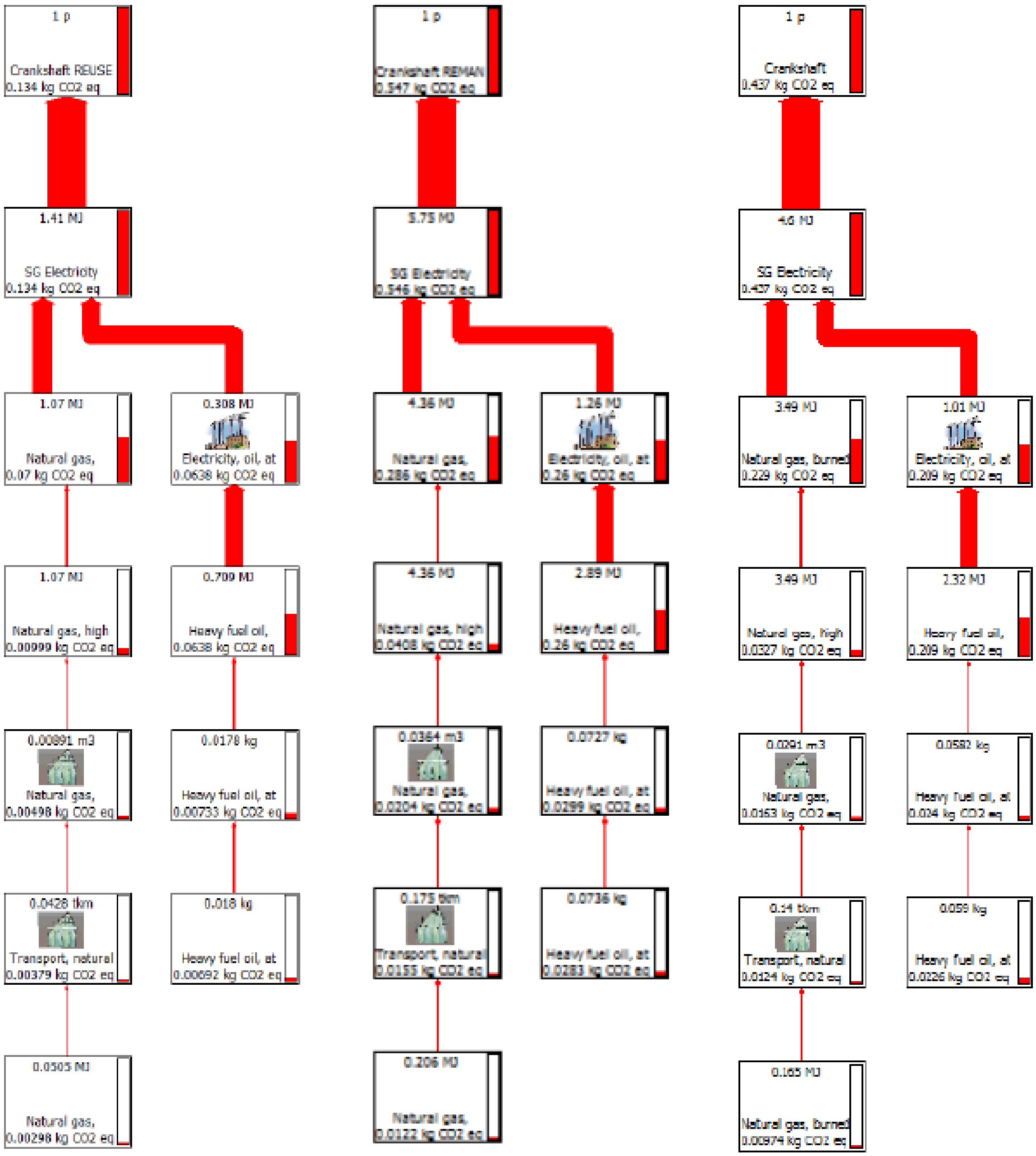
Process Network (Dispose) – 5% cutoff[1]



[1] cutoff is employed to filter processes which contribute insignificant to the overall environmental impact

CRANKSHAFT

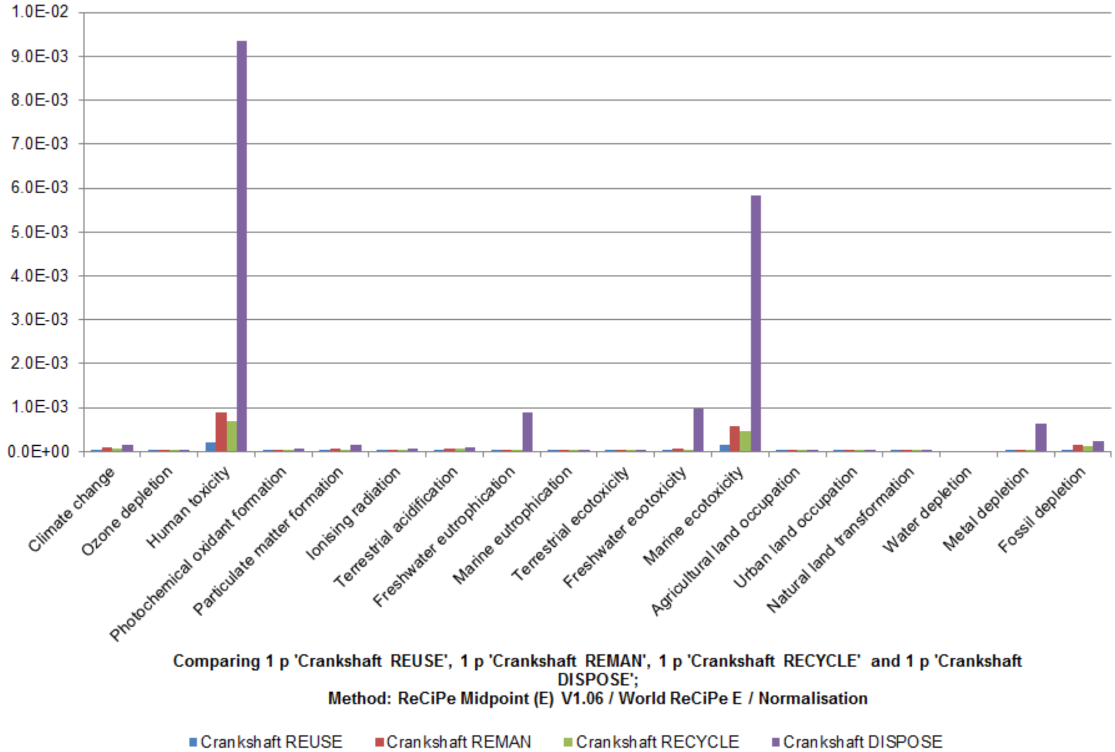
Process Network (Reuse, Remanufacture, Recycle) – 2% cutoff



B2: Environmental Impact Models (Simapro) - Crankshaft

CRANKSHAFT

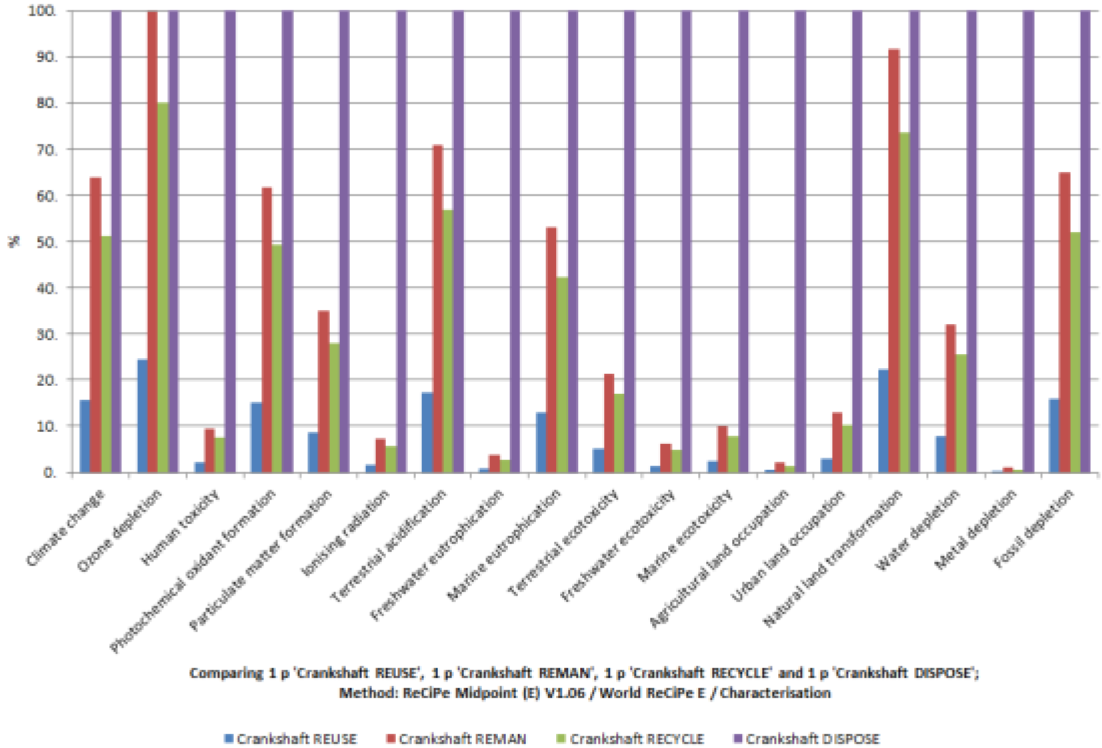
<u>Normalised Chart</u>



B2: Environmental Impact Models (Simapro) - Crankshaft

CRANKSHAFT

Characterised Chart



C1: Calculating the exponential constant

This table presents pairs of numbers $z_{0.5}$ and R that solve the equation

$$0.5 = \frac{1 - \exp(-\frac{z_{0.5}}{R})}{1 - \exp(-\frac{1}{R})}$$

$z_{0.5}$	R
0.00	-
0.01	0.014
0.02	0.029
0.03	0.043
0.04	0.058
0.05	0.072
0.06	0.087
0.07	0.101
0.08	0.115
0.09	0.13
0.10	0.144
0.11	0.159
0.12	0.174
0.13	0.189
0.14	0.204
0.15	0.22
0.16	0.236
0.17	0.252
0.18	0.269
0.19	0.287
0.20	0.305
0.21	0.324
0.22	0.344
0.23	0.365
0.24	0.387

$z_{0.5}$	R
0.25	0.410
0.26	0.435
0.27	0.462
0.28	0.491
0.29	0.522
0.3	0.555
0.31	0.592
0.32	0.632
0.33	0.677
0.34	0.726
0.35	0.782
0.36	0.845
0.37	0.917
0.38	1.001
0.39	1.099
0.4	1.216
0.41	1.359
0.42	1.536
0.43	1.762
0.44	2.063
0.45	2.483
0.46	3.112
0.47	4.157
0.48	6.243
0.49	12.497

$z_{0.5}$	R
0.5	Infinity
0.51	-12.497
0.52	-6.243
0.53	-4.157
0.54	-3.112
0.55	-2.483
0.56	-2.063
0.57	-1.762
0.58	-1.536
0.59	-1.359
0.6	-1.216
0.61	-1.099
0.62	-1.001
0.63	-0.917
0.64	-0.845
0.65	-0.782
0.66	-0.726
0.67	-0.677
0.68	-0.632
0.69	-0.592
0.7	-0.555
0.71	-0.522
0.72	-0.491
0.73	-0.462
0.74	-0.435

$z_{0.5}$	R
0.75	-0.410
0.76	-0.387
0.77	-0.365
0.78	-0.344
0.79	-0.324
0.8	-0.305
0.81	-0.287
0.82	-0.269
0.83	-0.252
0.84	-0.236
0.85	-0.220
0.86	-0.204
0.87	-0.189
0.88	-0.174
0.89	-0.159
0.9	-0.144
0.91	-0.130
0.92	-0.115
0.93	-0.101
0.94	-0.087
0.95	-0.072
0.96	-0.058
0.97	-0.043
0.98	-0.029
0.99	-0.014