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A NEW METRIC-BASED LCA METHOD FOR ASSESSING THE SUSTAINABILITY PERFORMANCE OF METALLIC AUTOMOTIVE COMPONENTS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Mechanical Engineering
in the College of Engineering at the University of Kentucky

By

Xiangxue Zhang

Lexington, Kentucky

Director: Dr. I. S. Jawahir, Professor of Mechanical Engineering

Lexington, Kentucky

2012

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ABSTRACT OF THESIS

A NEW METRIC-BASED LCA METHOD FOR ASSESSING THE SUSTAINABILITY PERFORMANCE OF METALLIC AUTOMOTIVE COMPONENTS

This thesis presents a new metric-based Life-cycle Assessment (LCA) method for assessing the sustainability performance of metallic automotive components. The unique feature of this research work include the development and use of a metrics-based product sustainability index (*ProdSI*) methodology by considering the total life-cycle approach and the triple bottom line (TBL) with the 6R methodology. It has been shown that the manufactured product's sustainability performance can be comprehensively assessed using this new methodology. The major focus of this research is the integration of the 6R activities (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture). Four life-cycle stages of the product, with various end-of-life (EOL) product scenarios, are modeled and analyzed. These scenarios include: reuse, remanufacturing, and recycling the products at EOL. Furthermore, a new mathematical model is developed and presented to determine the optimum percentage mix for various product EOL strategic options. By using the 6R methodology, the overall product sustainability was significantly improved. This improvement was quantitatively assessed by computing the *ProdSI* score. Ultimately, this research shows that a closed-loop material flow can be achieved.

KEYWORDS: Product Sustainability, 6Rs, Product Sustainability Assessment, Life-cycle Assessment (LCA), Product Optimization

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11/16/2012

A NEW METRIC-BASED LCA METHOD FOR ASSESSING THE SUSTAINABILITY PERFORMANCE OF METALLIC AUTOMOTIVE COMPONENTS

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Dedicated to my family: Grandma, Father, and Uncle

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TABLE OF CONTENTS

Acknowledgements iii

List of Figures vi

List of Tables ix

CHAPTER 1 Introduction 1

1.1 Product Sustainability Evaluation and the Product Sustainability Index (*ProdSI*) 1

1.2 The Framework of the Life-Cycle Assessment (LCA) Methodology 3

1.3 Life-cycle stages of Metallic Automotive Components 6

1.4 Scope of the Proposed Work 9

CHAPTER 2 Literature Review 10

2.1 Product Sustainability Evaluation 10

2.2 Life-Cycle Assessment 15

2.3 Product Optimization 17

2.4 Review Summary and Problem Identification 20

2.4.1 Review Summary 20

2.4.2 Problem Identification 22

CHAPTER 3 New Metric-based LCA Methodology 23

3.1 The 6R Methodology 23

3.1.1 Terminologies and Descriptions 24

3.1.2 The 6R Decision Flow 27

3.2 Product Sustainability Metrics and the Product Sustainability Index (*ProdSI*) Methodology 29

3.2.1 Product Sustainability Metrics 29

3.2.2 Product Sustainability Index (*ProdSI*) Methodology 33

3.3 The LCA Methodology 38

3.3.1 Description of the Methodology 38

3.3.2 Most Commonly Used LCA Methods 42

3.4 Summary 46

CHAPTER 4 Life-Cycle Modeling of Metallic Automotive Components and Mathematical Model for Product Sustainability Metrics 47
4.1 Life-Cycle Modeling of Metallic Automotive Components 52
4.1.1 Modeling the Reused EOL Product 52
4.1.2 Modeling the Remanufactured EOL Product 66
4.1.3 Modeling the Recycled EOL Product 81
4.1.4 Summary 97
4.2 Mathematical Model for Product Sustainability Metrics 98
4.2.1 Assumptions and Descriptions of the Model Formulation 98
4.2.2 Mathematical Model 99
4.2.3 Results and Discussion 103
4.2.4 Summary 105
CHAPTER 5 Conclusions and Future Work 106
5.1 Conclusions 106
5.2 Future Work 107
References 108
Vita 117

LIST OF FIGURES

Figure 1-1 Life-cycle stages in a LCA and typical inputs/outputs measured 3
Figure 1-2 Four basic elements and processes for a product LCA 4
Figure 1-3 A framework for a LCA and the interrelationships among four basic elements 6
Figure 1-4 Worldwide vehicle sales till August 2012 7
Figure 2-1 The focus areas of current methods for evaluating the product sustainability 21
Figure 3-1 6R concept for a near perpetual material flow in a closed-loop 24
Figure 3-2 The 6R decision flow diagram across four life-cycle stages of metallic automotive components 28
Figure 3-3 Elements/sub-elements of product design for sustainability..... 29
Figure 3-4 The structure of *ProdSI* and its sub-index components with their clusters..... 30
Figure 3-5 Sub-index, Economy, and its clusters 31
Figure 3-6 Sub-index, Environment, and its clusters..... 31
Figure 3-7 Sub-index, Society, and its clusters..... 31
Figure 3-8 The hierarchical structure of the *ProdSI* methodology and the assessment methods applied 33
Figure 3-9 The five-step hierarchical *ProdSI* evaluation process..... 33
Figure 4-1 Decision flow diagram across four life-cycle stages for reusing EOL products 52
Figure 4-2 Process map across four life-cycle stages for reusing EOL products 53
Figure 4-3 Variation curve for mass of hazardous material use at the PU stage of reusing EOL products 55
Figure 4-4 Variation curve for total mass of hazardous material use of reusing EOL products..... 55
Figure 4-5 Variation curve for energy use at the PM and M stage of reusing EOL products..... 57
Figure 4-6 Variation curve for total energy use of reusing EOL products 57
Figure 4-7 Variation curve for water use at the PU stage of reusing EOL products 59
Figure 4-8 Variation curve for total water use of reusing EOL products 59

Figure 4-9 Variation curve for GHG emission at the PU stage of reusing EOL products 61
Figure 4-10 Variation curve for total GHG emission of reusing EOL products 61
Figure 4-11 Variation curve for the total direct cost of reusing EOL products 65
Figure 4-12 Comparison for hard coal use at 20% vs. 90% ratio of reusing EOL product 66
Figure 4-13 Decision flow diagram across four life-cycle stages for remanufacturing EOL products 67
Figure 4-14 Process map across four life-cycle stages for remanufacturing EOL products 67
Figure 4-15 Variation curve for mass of hazardous material use at the PU stage of remanufacturing EOL products 69
Figure 4-16 Variation curve for total mass of hazardous material use of remanufacturing EOL products 69
Figure 4-17 Variation curve for energy use at the PM stage of remanufacturing EOL products 71
Figure 4-18 Variation curve for energy use at the PU stage of remanufacturing EOL products 72
Figure 4-19 Variation curve for total energy use of remanufacturing EOL products 72
Figure 4-20 Variation curve for water use at the PU stage of remanufacturing EOL products 74
Figure 4-21 Variation curve for total water use of remanufacturing EOL products 74
Figure 4-22 Variation curve for Greenhouse Gas emission at the PU stage of remanufacturing EOL products 76
Figure 4-23 Variation curve for total Greenhouse Gas emission of remanufacturing EOL products 76
Figure 4-24 Variation curve for the total direct cost of remanufacturing EOL products . 80
Figure 4-25 Comparison for water use at 20% vs. 90% ratio of remanufacturing EOL product 81
Figure 4-26 Decision flow diagram across four life-cycle stages for recycling EOL products 82
Figure 4-27 Process map across four life-cycle stages for recycling EOL products 82

Figure 4-28 Variation curve for mass of hazardous material use at the PM stage of recycling EOL products 84
Figure 4-29 Variation curve for mass of hazardous material use at the PU stage of recycling EOL products 84
Figure 4-30 Variation curve for total mass of hazardous material use of recycling EOL products 85
Figure 4-31 Variation curve for energy use at the PM stage of recycling EOL products 86
Figure 4-32 Variation curve for total energy use of recycling EOL products 87
Figure 4-33 Variation curve for water use at the PM stage of recycling EOL products .. 88
Figure 4-34 Variation curve for total water use of recycling EOL products 89
Figure 4-35 Variation curve for Greenhouse Gas emission at the PM stage of recycling EOL products 90
Figure 4-36 Variation curve for total Greenhouse Gas emission of recycling EOL products 91
Figure 4-37 Variation curve for the total direct cost of recycling EOL products 95
Figure 4-38 Comparison for carbon dioxide at 20% vs. 90% ratio of recycling EOL product 96
Figure 4-39 Combined loop for various EOL product strategic options 98

LIST OF TABLES

Table 3-1 6R definitions 25
Table 3-2 Individual metrics selected for the study 40
Table 3-3 Commonly used LCA impact assessment methods and tools 43
Table 4-1 Input parameters to the LCA software 49
Table 4-2 Mass of hazardous material use for various ratio of reused EOL product 54
Table 4-3 Energy use for various ratio of reused EOL product 56
Table 4-4 Water use for various ratio of reused EOL product 58
Table 4-5 Greenhouse Gas emission for various ratio of reused EOL product 60
Table 4-6 Cost data used in this study 62
Table 4-7 Labor cost for various ratio of reused EOL product 62
Table 4-8 Material cost for various ratio of reused EOL product 63
Table 4-9 Energy cost for various ratio of reused EOL product 63
Table 4-10 Water cost for various ratio of reused EOL product 64
Table 4-11 Total direct cost for various ratio of reused EOL product 64
Table 4-12 Mass of hazardous use for various ratio of remanufactured EOL product 68
Table 4-13 Energy use for various ratio of remanufactured EOL product 70
Table 4-14 Water use for various ratio of remanufactured EOL product 73
Table 4-15 Greenhouse Gas emission for various ratio of remanufactured EOL product 75
Table 4-16 Labor cost for various ratio of remanufactured EOL product 77
Table 4-17 Material cost for various ratio of remanufactured EOL product 78
Table 4-18 Energy cost for various ratio of remanufactured EOL product 78
Table 4-19 Water cost for various ratio of remanufactured EOL product 79
Table 4-20 Total direct cost for various ratio of remanufactured EOL product 79
Table 4-21 Mass of hazardous material use for various ratio of recycled EOL product .. 83
Table 4-22 Energy use for various ratio of recycled EOL product 86
Table 4-23 Water use for various ratio of recycled EOL product 88
Table 4-24 Greenhouse Gas emission for various ratio of recycled EOL product 90
Table 4-25 Mass of waste disposed for various ratio of recycled EOL product 92
Table 4-26 Labor cost for various ratio of recycled EOL product 93

Table 4-27 Material cost for various ratio of recycled EOL product 93
Table 4-28 Energy cost for various ratio of recycled EOL product 94
Table 4-29 Water cost for various ratio of recycled EOL product 94
Table 4-30 Total direct cost for various ratio of recycled EOL product 95
Table 4-31 Notations used in the formulation of the mathematical model..... 99
Table 4-32 Mathematical model set-up in Excel sheet..... 103
Table 4-33 Results for different weights assigned..... 104

CHAPTER 1

INTRODUCTION

In this chapter, an outline of the thesis chapters is introduced. Section 1.1 presents the concepts of product sustainability evaluation and the methodology involved in developing the product sustainability index. Section 1.2 presents the framework of the Life-cycle Assessment methodology. Section 1.3 presents four life-cycle stages of metallic automotive components. Section 1.4 defines the scope of this thesis work.

1.1 Product Sustainability Evaluation and the Product Sustainability Index (*ProdSI*)

Since the concept of sustainable manufacturing has been accepted as a leading industrial culture for over three decades ago, achieving the overall sustainability in the entire industrial world is well recognized. The implementation of sustainable manufacturing practices in order to produce sustainable products has in recent times emerged as a necessity for competitive manufacturing. Sustainable products are generally defined as those products that provide economic, environmental and societal benefits, while maintaining and/or enhancing the quality and performance across their entire life-cycle, from the extraction of raw materials to the end-of-life disposition (Datschefki, 1999). This concept also indicates the correlation among financial benefits, environmental soundness and societal wellbeing. Economy, environment, and society are considered as three major elements of product sustainability, known as the Triple Bottom Line (TBL). These three major components are interrelated and integrated via technology and human resources (Jawahir et al., 2006). The manufacturing processes for manufactured products also require full consideration and assessment with respect to the impacts of these three major areas. Furthermore, in order to manufacture more sustainable products, it is crucial to expand the design and the manufacturing processes from the traditional approaches to include and span the entire product life-cycle, including pre-manufacturing (PM), manufacturing (M), use (U), and post-use (PU) stages (Jawahir et al., 2006). For the purpose of minimizing a product's ecological footprint and improving the product's

sustainability, the “6R” methodology (Reduce, Reuse, recycle, Recover, Redesign and Remanufacture) was developed by transforming the traditional “3R” concept (Reduce, Reuse, and Recycle). Ultimately, a near-perpetual product/material flow can be achieved from the perspective of multiple life-cycles (Jawahir et al., 2006)

When it comes to the product sustainability, six major elements and their sub-elements involved in the Design for Sustainability (DfS) (environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact) are considered as the guidelines for the development of a comprehensive set of product sustainability metrics (Jawahir et al., 2006). This set of metric system serves as the basis of the proposed new metric-based methodology for evaluating the product sustainability. In order to comprehensively assess the sustainability behavior and the sustainability performance of a manufactured product, the product sustainability metric system and the proposed methodology for evaluating the product sustainably assessment have simultaneously considered TBL, total product life-cycle, the 6R methodology, and the six elements of DfS. This new methodology is generic that it can be applied to a range of manufactured products. The metric system is customizable for different products.

Based on the comprehensive set of product sustainability metrics, the product sustainability index, known as the *ProdSI*, is developed to evaluate the sustainability behavior and the sustainability performance of manufactured products. It has a sequenced, five-level hierarchical structure: individual metrics, sub-clusters, clusters, sub-index, and the *ProdSI*. This evaluation approach includes a series of operation procedures – data normalization, weighting and score aggregation. Data normalization is applied to convert measured physical data into dimensionless scores that each metric specifies. Weighting factors are assigned according to the importance of that metric. The normalized data is finally aggregated to generate a *ProdSI* score to represent the actual sustainability content in the product (Zhang et al., 2012).

1.2 The Framework of the Life-Cycle Assessment (LCA) Methodology

For addressing environmental issues specifically, the life-cycle thinking/concept has been incorporated into the product development stage. Ultimately, it has become the backbone in the new industrial culture for sustainable production (Alting and Jorgensen, 1993). Many business enterprises are improving their environmental performance by means of pollution prevention strategies and environmental management systems, for the sake of minimizing the effects to the environment throughout the products' entire life-cycle (Curran, 1996). To assess the outcomes of achieving such a goal, a unique holistic approach – the Life-cycle assessment (LCA) methodology – enables the assessment of the associated consequences caused by a manufactured product throughout its four life-cycle stages (Wenzel et al., 1994). Furthermore, according to the ISO 14040 standard, a LCA is defined as the 'compilation and evaluation of inputs, outputs and potential environmental impacts of a product system or service throughout its total life-cycle" (ISO14040, 2006). Figure 1-1 illustrates the four life-cycle stages that are considered in a typical LCA with inputs and outputs measured.

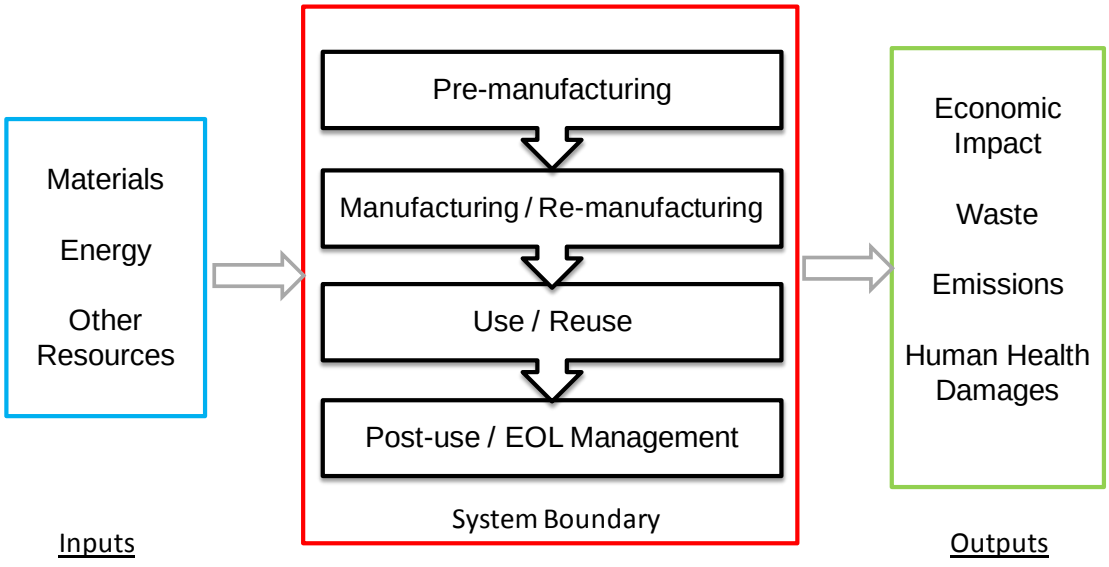

Figure 1-1 Life-cycle stages in a LCA and typical inputs/outputs measured

(Source: EPA, Life Cycle Assessment: Principles and Practice, 2006)

LCA is a technique that assesses the environmental aspects of a manufactured product and the potential impacts related to that particular product. To be more specific, this method assesses the potential impacts associated with the identified inputs and outputs, based on the inventory of inputs (materials, energy and other resources) and outputs (economic impact, wastes and emissions, and human health damages). It can provide a visual evaluation of the environmental impacts and resource consequences resulting from the decisions made in the product development phase. Those decisions could be related to product concept, product structures, material selections and manufacturing processes. Finally, the results provide a guidance for decision-makers to make more reliable and more informed decisions. Therefore, by considering the impacts across the product's entire life-cycle, the LCA provides a broad view of the environmental effects of the manufactured product, and it also gives more accurate guidelines for product and process selection with the respect to environmental trade-offs.

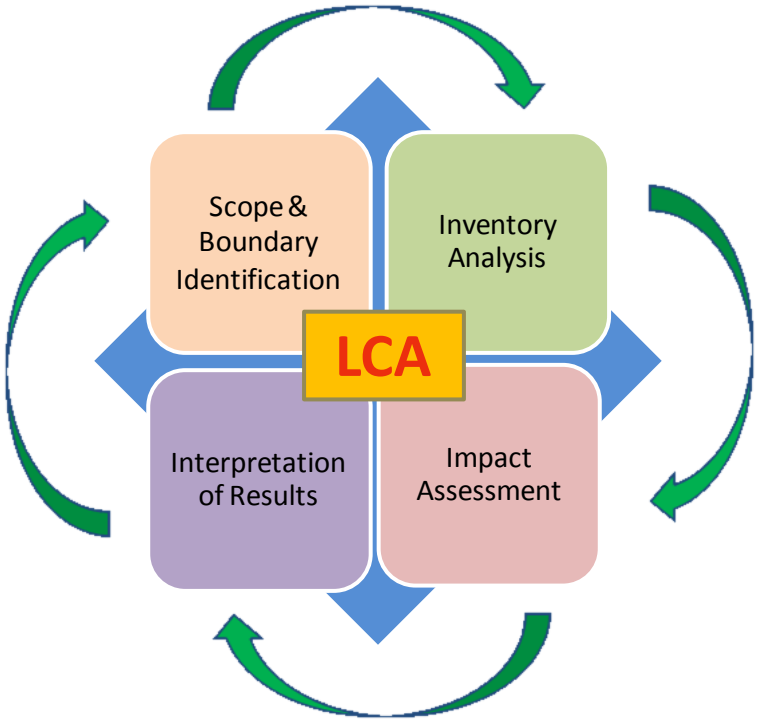

Figure 1-2 Four basic elements and processes for a product LCA

A product life-cycle assessment is a systematic approach. Four basic elements are included: scope and boundary identification, inventory analysis, impact assessment and interpretation of evaluated results (Consoli, 1993), as shown in Figure 1-2. In the phase of scope and boundary identification, the scope of the study is established and research boundary is determined. It includes the selection of a functional unit for the environmental performance to be measured and to be evaluated. It also includes the identification of the life-cycle stages and the system boundary (EPA, Life Cycle Assessment: Principles and Practice, 2006). In the phase of inventory analysis, all input and output metrics are identified. An inventory of input and output data across the product's four life-cycle stages are measured and collected, in terms of material consumption, energy and other resources used, economic impact, wastes and emission, and human health impact. These baseline data are subsequently quantified and evaluated for the third phase of a LCA for impact assessment. By integrating the LCA method into the product sustainability index (*ProdSI*) methodology, the product sustainability index score is calculated from the inventory data to analyze the sustainability performance of metallic automotive components. At the final phase of a LCA, the severity of the impacts, the strength and weaknesses of the product sustainability can be represented. Objectives of the phase of result interpretation are to identify the serious issues resulting from the manufactured products and the related processes, draw conclusions and give recommendations. A framework for a LCA and the interrelationships among these four basic elements are shown in Figure 1-3.

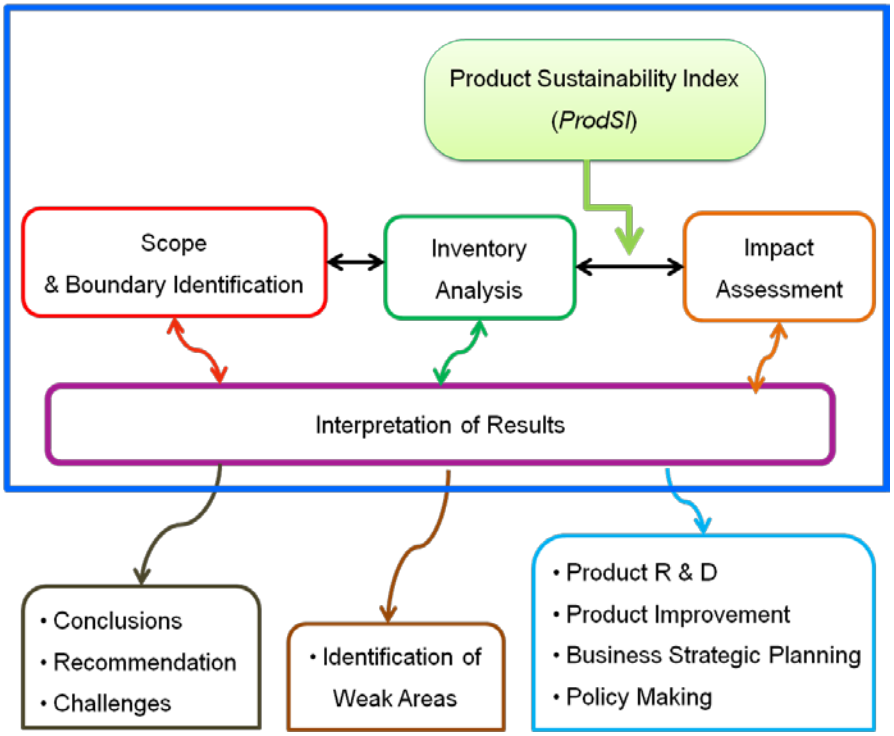

Figure 1-3 A framework for a LCA and the interrelationships among four basic elements

1.3 Life-cycle stages of Metallic Automotive Components

Automotive industry is one of the largest consumer product segments that continue to grow. From January 2011 to August 2012, more than 684 million vehicles were registered worldwide. It accounts for 8% of growth compared with the total sales of the previous year, as shown in Figure 1-4. United States shares nearly 20% of this worldwide record, even though the US represents only 4.5% of the world's population.

The increasing growth of the automotive market has raised serious concerns about the significant burden caused by the vehicles. Tremendous efforts have been made in improving the sustainability of automobiles at a full life-cycle perspective.

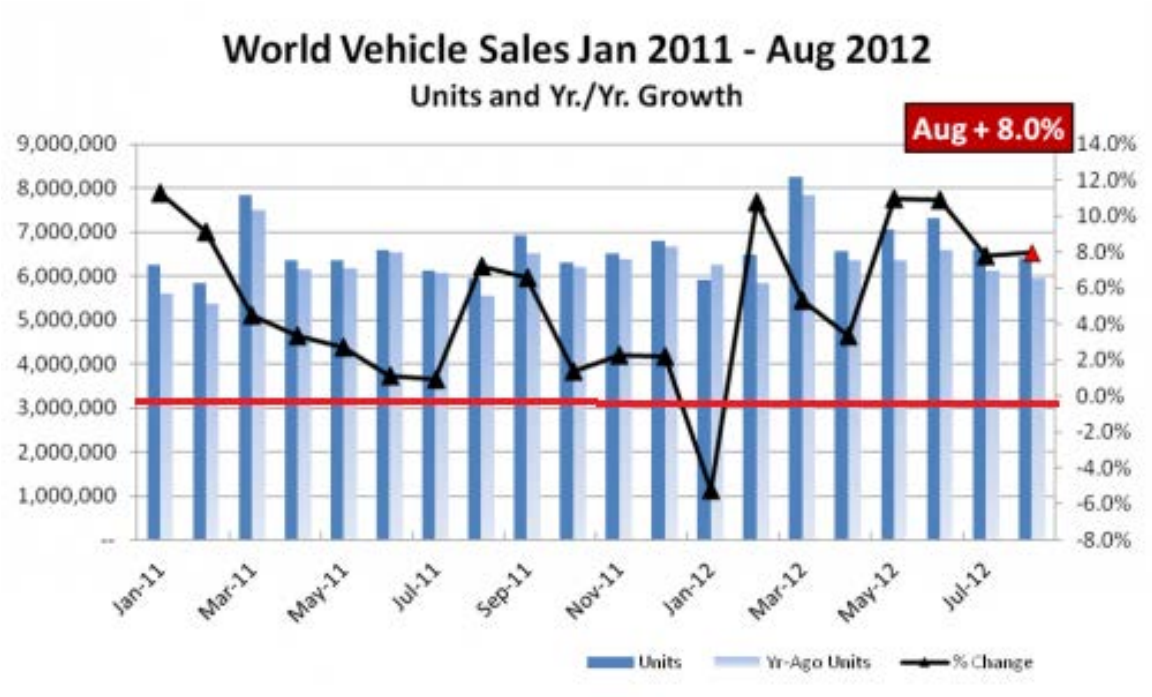

Figure 1-4 Worldwide vehicle sales till August 2012

(Source: (World Vehicle Sales, August 2012, WARDSAUTO)

A typical vehicle has approximately twenty thousand components. All of these parts and their final assembled automotives experience a full life-cycle: materials processing; manufacturing, including part fabrication and vehicle assembly; use, associated with the operation and service of the vehicle; and finally, the end-of-life vehicle management. Among these stages, several key issues are specially emphasized - material type, material mass, and fuel efficiency of the powertrain. Since the overall sustainability performance of an assembled product can be improved by improving the sustainability of its components (Gao et al., 2003). Consequently, by using light-weight materials, changing material composition, reusing, remanufacturing, and recycling, EOL vehicles have become the main research topics for the sustainability of automobiles.

Pre-manufacturing (PM) Stage

The life-cycle of an automobile and its components start at the PM stage, involving raw material extraction and preliminary material manufacturing processes. To be more specific, this stage includes the activities of mining operations, transporting the virgin ores from their mining sites to the first refining plant for material fabrication. At this stage, the energy and greenhouse gas are highly intensive because of mining operations and ore refining practices. These environmental unfriendly processes lead to burdens to the environment and the society. If the component is made of virgin material, it highly depends on the availability and concentration of primary resources coming from the Earth's crust. Due to the scarcity of resources, it is urged to use the recycled materials instead of virgin material at this stage.

Manufacturing (M) Stage

The M stage of the vehicle comprises two separate options: component manufacturing and vehicle assembly. For metallic automotive components, shape-forming processes, transport, painting and galvanizing the vehicle surfaces can be involved. In terms of energy and material consumption, the M stage is not as much intensive as the PM stage.

Use (U) Stage

For energy consumption, the U stage is the biggest contributor among four life-cycle stages of a vehicle. Two elements can be considered: vehicle operation and service for maintenance and repair. There are multiple ways to reduce the footprints in terms of the vehicle operation: using light-weight materials, reducing the vehicle sizes, and improving powertrain technology.

Post-use (PU) Stage

When the useful life of a vehicle comes to an end, several recovery processes for retired automobiles can be considered. Reuse or remanufacture the components such as engines and motors, and materials recycling. Automobiles are one of the most-recovered consumer products. About 95% of ELVs enter the auto-recovering system. Majority of these old vehicles are initially processed by dismantlers to remove components that are recoverable for reuse and remanufacture. The remaining portion of the vehicle will to be sent to a shredder to recover about 95% of the ferrous and nonferrous metals from the auto bodies.

1.4 Scope of the Proposed Work

This research thesis presents a new metric-based LCA methodology to comprehensively evaluate the sustainability of all manufactured products. This new methodology considers three major aspects of the product sustainability, a total life-cycle approach, elements/sub-elements of Design for Sustainability, and the 6R methodology.

Furthermore, main emphasis of this research study is to incorporate the 6R activities into the modeling of four life-cycle stages of metallic automotive components. The overall product sustainability is expected to show improvements by using the 6R methodology. Finally, the product sustainability can be quantitatively assessed by using the *ProdSI* score, and improvements can be made accordingly for the next generation of products

CHAPTER 2

LITERATURE REVIEW

Research on developing new methodologies for product sustainability evaluation, Life-Cycle Assessment, and optimization started over two decades ago. Since then, much research work has been done, but not very systematically or well-coordinated way. The focus in this literature review is to briefly review the research development and the applications of these methodologies. This chapter is structured as follows: First, the product sustainability evaluation, where the focus is on the development of various frameworks and assessment methodologies. Second, the LCA method, where the emphasis is on product life-cycle assessment. Third, a comprehensive review of the recent optimization methods, where the focus is on the optimization methodology applied to manufactured products. Finally, a summary of the literature review is given along with a statement of problem description for the proposed research study.

2.1 Product Sustainability Evaluation

Early work by Fiksel et al. (Fiksel et al., 1998) present product sustainability indicators based on the previous practices in the leading companies. These industrial practices were focused on economic, environmental and societal performance evaluation individually. The product sustainability indicators indicate the major aspects of the product sustainability - economy, environment, and society - across full life-cycle stages of a product. An approach towards integration of three elements of product sustainability was presented in this paper, where the proposed indicators formed a framework for measuring the comprehensive sustainability performance. The sustainability target method (STM), developed by Dickinson and Caudill (Dickson and Caudill, 2003), established correlations between a manufactured product's environmental impacts and its economic value. Based on relevant indicators, STM computes resource productivity and eco-efficiency. It provides a practical sustainability target by using the estimations of the earth's carrying capacity and economic information. It helps to predict whether the end-of-life option is feasible for a particular product. Based on the indicators in the STM,

components that have better performance among various vendor suppliers can be selected by a company. Gao et al. (Gao et al., 2003) applied the STM method to develop a formulation to choose the most sustainable component for a product assembly system. A sustainability scoring method, developed by de Silva et al. (de Silva et al., 2006), was used to present the sustainability performance of an electronic product. This method considers six sustainability elements: environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact. Each of these elements is further classified into various corresponding sub-elements. Depending on the importance of these sub-elements, different levels of influencing factors are assigned - high, medium, or low importance. Finally, comprehensive sustainability scores are computed by considering all major product sustainability elements and sub-elements. Based on the available data provided by the original equipment manufacturer and the product end-of-life recyclers, weightings were assigned according to design requirements customer expectations. This method can also be used as a tool to compare similar products. This sustainability scoring method was further developed and applied by Ungureanu et al. (Ungureanu et al., 2007) to quantitatively assess the potential benefits of an aluminum alloy, a light-weight material, used in the manufacturing of an autobody. Based on the six major elements and their sub-elements of the Product Design for Sustainability to autobody application, influencing factors were categorized according to their levels of importance to the product. Finally, the use of two different materials (steel alloy and aluminum alloy) was compared for sustainability performance. A framework for sustainability assessment tools, proposed by Ness et al. (Ness et al., 2007), categorizes some of the most commonly used sustainability assessment methods into three major groups, based on the dimension and the object of focus. Major assessment methods are related to indicators/indices, LCA, LCC, product material flow analysis, product energy analysis, and product-related assessment. A framework for developing product sustainability indices was proposed by Bohringer et al. (Böhringer et al., 2007). The evaluation techniques of those indices were also presented. A large range of indices considered include living planet index, ecological footprint, city development index, human development index, environmental sustainability index, environmental performance index, environmental vulnerability index, index of

sustainable economic welfare and genuine progress indicator, well-being assessment index, genuine savings, and green net national product & system of integrated environmental and economic accounting (SEEA). An infrastructure for assessing the sustainability performance of companies, proposed by Singh et al. (Singh et al., 2009), covers various indicators and indices for sustainability. Two mainstreams of the sustainability assessment methodology were addressed: economy-related and physical indicator-related. Frameworks for various retrospective indicators and indices were also discussed and their focus points were compared. Guidelines for constructing the indices were given. Methods for evaluating sustainability indices were presented, including data scaling, normalization, weighting and data aggregation. The infrastructure for sustainable manufacturing measurement, proposed by Feng and Joung (Feng and Joung, 2009) can be considered as a foundation for decision-making tools in the development of business strategies. The proposed infrastructure covers three key components, which are sustainable indicator repository, sustainability measurement methodologies, and performance report. These major components of the sustainability measurement infrastructure are interrelated with each other. The comprehensive set of sustainability metrics, proposed by Gupta et al. (Gupta et al., 2010), includes a new framework for manufactured products. A methodology that prioritizes some of the metrics according to their importance was presented. The method is aimed at overcoming the difficulties of evaluating a large scale of data. The infrastructure for developing a comprehensive product sustainability metrics, proposed by Feng et al. (Feng et al., 2010), also enables quantitative measurement of sustainability performance of a manufactured product. This infrastructure enables to measure a product's sustainability throughout its entire life-cycle. Several key components are considered in the development of product sustainable performance metrics, which are definitions, indicators, sustainable performance characteristics, needs, and reasons for sustainable measurements, and available sustainability analysis tools. A set of indicators called Sustainable Manufacturing Indicator Repository (SMIR), presented by Sarkar et al. (Sarkar et al., 2011), provides a web-based, open, and neutral platform to be accessible by small and medium sized manufacturing enterprises. The SMIR is based on an integrated and an extended version of thirteen sustainability indicators. The repository has five dimensions of sustainability:

environmental stewardship, economic growth, social well-being, technological advancement, and performance management. This set of indicators provides a helpful insight on sustainability for manufacturing processes, manufactured products, and organizations. A set of initial key performance indicators (KPIs) for sustainable manufacturing evaluation was proposed by Amrina and Yusof (Amrina and Yusof, 2011). The KPIs consider three major aspects of the product sustainability. It has nine elements and forty one sub-elements. The set of sustainability indicators was developed specifically for automotive industry. A weighted fuzzy approach - Weighted Fuzzy Assessment Method (WFAM), developed by Ghadimi et al. (Ghadimi et al., 2012), can mathematically assess weights to selected elements and their sub-elements. The steps of proposed methodology are two folds: a Fuzzy analytical hierarchy process is used to assign weights to selective elements and their sub-elements; and based on the acquired weights, the product sustainability is further assessed by using fuzzy logic method.

In the industrial world, many manufactures have developed associated methods for assessing the sustainability of their products. A product sustainability index (PSI) method, developed by Schmidt and Butt (Schmidt and Butt, 2006), includes eight (8) key indictors across three major components of the product sustainability. The environmental indicators are selectively used from LCA impact assessment categories. The economic indicators are based on Life-Cycle Costing (LCC) assessment. And, the societal indicators are to assess the safety and mobile capability of the product. In the following year, the methodology was applied by Ford to assess the sustainability performance of their two automobile models: Ford S-MAX and Ford Galaxy. The goals of performing the PSI method were three folds: It was aimed at assessing the environmental impacts introduced by the products, measuring the economic benefits the product had brought to the company, and analyzing the issues related to safety and health (Ford Product sustainability index Report, 2007). Metrics for green sustainable manufacturing was developed and introduced by General Motors (GM) in 2009 (Dreher et al., 2009). The development of the metrics is based on a survey of existing literatures and the best practices in automotive industries. A total of thirty-three (33) metrics was introduced. They were aggregated into six major areas: environmental impact, energy consumption,

personal health, occupational safety, manufacturing costs and waste management based on the early work at the University of Kentucky (Jawahir and Dillon, 2007). The objectives for developing the metrics were to establish an indication to improve the product sustainability and to set standards for industry-wide practices. With the collaboration with organizations, countries and business groups worldwide, OECD generated a toolkit that has eighteen (18) key indicators to measure the sustainability of manufacturing. It provides a general framework for the calculation of sustainability(OECD Sustainable Manufacturing Toolkit 2011). Launched in 1999, the Dow Jones Sustainability Index (DJSI) (Dow Jones Sustainability World Indexes Guide Book, 2011) tracks the criteria carried out by the world's leading companies with respect to economy, environment, and society. The indices enable business investors to integrate the considerations for sustainability into their portfolios. They provide an effective platform for those companies who would like to engage sustainability into practices.

For improving recovery and reuse of the end-of-life vehicles (ELVs), driven by the regulations, a minimum requirement of resource recovery must be at least 95% of the average weight per vehicle and year, while the energy recovery must be minimum of 10% of the average weight per vehicle and year, according to The European Directive 2000/52/CE (EU, 2000). Some recent work has been done with the regard to improving the sustainability performance of vehicles through emphasizing the EOL practices. Keoleian and Sullivan performed a life-cycle assessment and life-cycle costing assessment to analyze various materials used in automotive applications (Keoleian and Sullivan, 2012). This research was done by considering the four life-cycle stages of the vehicle. Because the product’s life-cycle and associated material selection, sourcing, and design decisions was a complex system, a large-scale optimization problem was presented in order to explore the role of materials in the sustainability of automobiles. The problem has multiple objectives and constrains. The results showed improvements to the automobile’s sustainability, by reusing, remanufacturing, and recycling the EOL products. A life-cycle assessment was performed by Holmberg and Argerich (Holmberg and Argerich, 2012) to a metallic automotive component. It quantitatively evaluates the

environmental impacts between the product made with virgin material and the one was remanufactured.

2.2 Life-Cycle Assessment

Life-cycle assessment is a relatively mature methodology that assesses the impacts of a specific area of the product sustainability – environment.

An internal study by The Coca-Cola Company in 1969 laid the foundation for the current methods of life-cycle analysis in the United States. The beverage container contributed the least environmental impacts was selected by comparison among various options. The study quantitatively assessed the use of raw materials and fuels, and the environmental burdens from the manufacturing processes of each container (The Coca-Cola Company, Sustainability-Reduce). With the growing attention to the environmental effects, the life-cycle thinking/concept was incorporated into product design and industrial production. Early work by Alting and Jorgesen (Alting and Jorgensen, 1993) addressed the importance of considering the entire life-cycle stages of a product. A conceptual framework - called the Life-Cycle Center - involving LCA were introduced. The proposed framework was aimed at developing concepts, methods, tools and technical solutions to produce more sustainable industrial products. In order to reduce ecological burdens, a conceptual framework for integrating life-cycle engineering into designing low energy consumption in the use phase of a product was introduced by Alting and Legarth (Alting and Legarth, 1995). The study was focused on the methods and tools for design for disassembly and design for recycling. Consequently, natural resources can be reutilized multiple times. Life-cycle assessment approach was later widely applied in various applications.

An Economic Input-Output Life-cycle Analysis model, developed by Maclean, H. (Maclean, 1998), was used to generate a large array of indicators for analyzing the economic and environmental impacts of a product. The assessment was carried out in the application of a midsized automobile. A life-cycle inventory analysis was performed by

Joshi (Joshi, 2000) by focusing on the manufacture and the use stages. A new model for performing product life-cycle assessment was presented. The analytical model proposed is a matrix, which consists typical environmental impact categories in conjunction with nearly five hundreds of economic inputs and outputs for the U.S. The proposed methodology is a practical and flexible tool that it can be applied to assessing individual products, comparing the same family products or new products. A complete life-cycle assessment case study on HP C4127X toner cartridge was performed by Berglind and Eriksson (Berglind and Eriksson, 2002), including life-cycle inventory analysis, characterization, weighting, sensitivity analysis, and result comparison. The emphasis of the study was on end-of-life alternatives. Two simplified semi-quantitative life-cycle assessment methods - environmentally responsible product assessment matrix (ERPA-matrix) and MECO-method, developed by Hochschorner and Finnveden (Hochschorner and Finnveden, 2003), were aimed at reducing the load for huge data collection. In order to compare the advantage and drawbacks of each method, both methods were applied to an electric and a petrol (gas-driven) car. A life-cycle indexing system (LInX), proposed by Khan et al. (Khan et al., 2004), incorporates LCA methodology in process and product evaluation and decision-making. The LInX developed has four sub-indices: EHS (environment, health and safety), cost, technical feasibility, and socio-political factors. Each index includes various numbers of basic parameters - EHS index has 11 parameters, cost index has 3, technical index has 4, and the socio-political index has 4 parameters. The LInX indexing system was developed to assist processes and products at the design stage. A three-leveled methodology was proposed for assessing a product's sustainability performance. The parameters and the indices are grouped and computed from level one to level three. Sub-indices can be obtained from combining basic parameters in each category at the first level. Sub-indices of each category are further grouped into a single index. At the final level, an overall index can be obtained from grouping four indices. Throughout the calculation, different weights – obtained by using expert option survey and analytical hierarchy process - were assigned to parameters and indices.

A new methodology involving total life-cycle cost analysis was proposed by Ungureanu et al. (Ungureanu et al., 2007). It was aimed at developing a new sustainability model to

quantitatively evaluate the total direct cost throughout the entire life-cycle of a vehicle. Evaluating the environmental impact caused by a light-weight material used for auto bodies was presented. A life-cycle engineering approach was applied by Ribeiro et al. (Ribeiro et al., 2008) to determine the material selection for a fender. The study considered the functional performance required by the fender together with the economical and environmental impacts. For evaluating and selecting the 'best' material for the fender, three different methods – LCC, LCA and a conventional approach - were applied to evaluate the sustainability performance of the product. Vinodh and Rathod (Vinodh and Rathod, 2010) applied the Environmentally Conscious Quality Function Deployment (ECQFE) to an electric vehicle. The study was to examine and determine the potential improvement that can be made at the design stage. Their work was phases-based. Based on the items in their engineering metrics, important parts most likely to affect the sustainability of the electric vehicle were identified. Design changes were estimated. Finally, the effect of design changes was translated to product improvements. An infrastructure, proposed by Heijungs et al (Heijungs et al., 2010), expands the conventional LCA framework to incorporate three major components of the product sustainability. The proposed framework has eight models to assess the sustainability of a product: micro-economic models, meso- and macro-economic models; cultural, institutional and political models; ethical and societal values; and models for integrated environmental, economic and societal analysis. The proposed framework emphasizes the interaction between environmental systems and the economic system.

2.3 Product Optimization

In general, optimization at a product level is aimed at providing one or multiple optimal results to issues such as the lowest cost, highest customer satisfaction, lowest environmental impact, highest performance, etc. Most previous work was related to finding the optimal materials or to configuring the optimal product designs and shapes.

An automobile recycling dynamic model - Disassembly Model Analyzer (DMA), developed by Zamudio-Ramirez (Zamudio-Ramirez, 1999), is an optimization program

that interprets the complex economic and physical information of products. It incorporates prices, physical flows, and the industry participants' decision processes, such as virgin and recycled material, automobile composition, flows of vehicles, and cost structures. A systematic analysis to the areas of product optimization was carried out by Burgard and Schlattmann (Burgard and Schlattmann, 2001). It was emphasized that technical optimization of products should be considered together with the economical aspect. It is because the adaptation of qualities to meet the customer's expectations should be considered together with the company's self-interest. The work conducted by de Weck et al. (de Weck et al., 2003), was focused on choosing the optimal number of product platforms to maximize the profit of a product family. Ma et al. (Ma et al., 2006) proposed a new eco-value based optimization methodology integrated life-cycle analysis with product optimization. This integration into a modular product design shows that life-cycle involving optimization has some significant advantages in product sustainability enhancement. The semantics-based method can be adaptable to any sustainability issues. A systematic mapping method, proposed by Wang and Ma (Wang and Ma, 2007), was to establish the interrelationships among different customer requirements and different quality specifications. The weights of various customer requirements and product quality characteristics were established by using the Analytic Network Process (ANP) approach. A combinatorial optimization problem for structuring of a notebook computer was presented by Zhou et al. (Zhou et al., 2007). Based on the evaluation to the product quality and product desirability, the component configuration was determined from achieving the lowest purchase cost while getting the highest customer satisfaction. The problem was solved via GA method. A research study also referred in the work was to maximize the shared surplus model through a product portfolio planning, and the interaction between customers and engineers.

Based on the sustainability index system developed, Wang and Lin (Wang and Lin, 2007) presented a sustainability optimization model to analyze the sustainability performance of decisions made, by finding the optimum solution involving various economic spending and value added. The sustainability index system itself involves three major aspects of the product sustainability; but the optimization method was applied to incorporate among

economic elements. Optimization methodology was applied to several studies to find optimal configuration for automobiles. Multidisciplinary optimization of autobodies with respect to car crash and noise, vibration, and harshness (NVH) was studied by Duddcck at the BMW Research Center (Duddcck, 2008). A multilevel multidisciplinary design optimization approach, developed by Ferguson et al. (Ferguson et al., 2009), was used to determine the major architectures for a family of three reconfigurable vehicles, involving a number of adaptable design variables. Quite a few research studies were focused on selecting optimal materials with the assistance of optimization methods. With the use of optimization approach, a study conducted by Ribeiro et al. (Ribeiro et al., 2008) showed some good results on finding the best material for a type of automobile fender among several material options, from mild steel to ultra strength steel, and aluminum alloys. By assessing material market cost, life-cycle cost, other additional costs, and environmental impacts, the optimal material was finally selected for that specific fender. The study further emphasized the importance of analyzing a product on its life-cycle perspective. In the study by Zhou et al. (Zhou et al., 2009), the optimal material with the highest total fitness value was selected for a drink container. Its environmental effects were analyzed through a product life-cycle assessment. Ultimately, the optimized mechanical, economic and environmental properties were achieved via methods of genetic algorithms (GA) and artificial neural networks (ANN). The results of their research concluded that both physical and chemical material interactions, manufacturability, post-use processing capabilities of that product might need to be considered in order to achieve a comprehensive level of analysis. A mathematical model, proposed by Huang et al. (Huang et al., 2012), achieved the maximized profit and customer's satisfaction, while the minimized energy consumption was obtained. The problem was solved by using a goal programming-based approach. Also, in this study, environmental impacts were analyzed and the effects were considered across the product's entire life-cycle.

2.4 Review Summary and Problem Identification

2.4.1 Review Summary

For the product and product sustainability evaluation, previous studies were not compressive. Figure 2-1 illustrates the focus areas of the current methods for the product sustainability evaluation. On the one hand, they were focused on a single or multiple life-cycle stages of the products, instead of four life-cycle stages. Emphasis was mainly on the manufacturing and the use stages. For example, original equipment manufacturers would most likely place their efforts on the manufacturing stage. Service providers would emphasis on the use stage of the type of products they are responsible for. On the other hand, their emphases were mostly on only one or two major areas of the product sustainability. Environmental impact assessment and life-cycle assessment, for instance, are good examples of assessing environmental impact of the products. However, they cannot be conclusive. There is a need for developing a novel and comprehensive methodology for product sustainability evaluation based on all prevalent metrics.

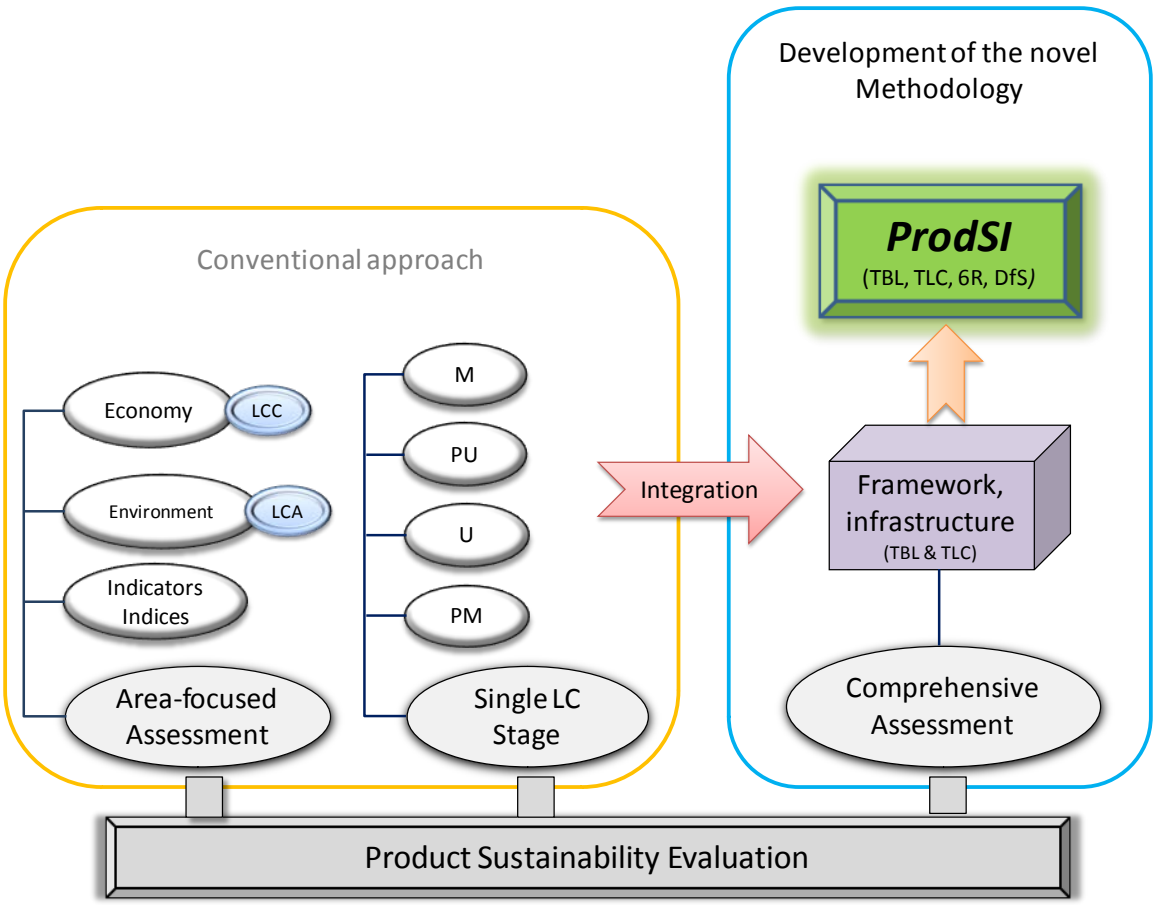

Figure 2-1 The focus areas of current methods for evaluating the product sustainability

Optimization approaches are widely applied to various industries and in specific applications. Many studies have been done on product optimization; but they are on a macro-level. To be more specific, those studies attempted to obtain optimal product configuration and material selection from optimization models at the product development stage. These studies were mostly focused on the design, manufacturing and use aspects of a product where the material or physical shape was analyzed for mechanical and economical performance. However, none of the research so far addressed any specific details about optimizing individual input parameter needed (i.e., material consumption, energy use, other resources, etc.), nor did they make any connections with the triple bottom line. These critical issues largely would lead to an open-loop of material

flows and isolated assessments. Consequently, research outcomes are probably unreliable to provide comprehensive guidelines for historic assessments and evaluations.

2.4.2 Problem Identification

Based on the above research review of previous work, only a little work has been done with regard to assessing the product sustainability comprehensively. And very few cases focused on improving the product sustainability throughout the entire life-cycle stages, especially including the PU stage. With the consideration of the TBL, total life-cycle approach, Design for Sustainability, and the 6R methodology, the objectives of this present research study are to develop and demonstrate a comprehensive methodology for evaluating the product sustainability, and to show how these approaches come together to play an important role in the improvement of the overall product sustainability.

CHAPTER 3

NEW METRIC-BASED LCA METHODOLOGY

In this chapter, a new metric-based LCA methodology is presented. This chapter is structured as follows: Section 3.1 presents the 6R methodology, including the terminologies and the 6R decision flow. Section 3.2 presents the product sustainability metrics and the Product Sustainability Index (*ProdSI*) methodology, including its five-level hierarchical structure and the evaluation methods applied to each step of the assessment process. Section 3.3 presents the methodology for Life-cycle Assessment. Its four basic segments and the most common assessment methods are addressed. At the end, in Section 3.4, a summary of this chapter is presented.

3.1 The 6R Methodology

Traditional ways to reduce footprints of a manufactured product after it reaches the end of valuable life are to recover or to reuse it. The 6R methodology has transformed the conventional 3Rs (reduce, recover, and reuse) to – reduce, recover, reuse, remanufacture, recycle, and redesign. This novel methodology has expanded the product EOL concepts; ultimately, multiple product life-cycles, instead of a single life-cycle can be achieved. Figure 3-1 illustrates this transformation and a near-perpetual material flow. Figure 3-1 also shows the entire life-cycle consisting of four stages: PM – Pre-manufacturing; M – Manufacturing; U – Use; and PU – Post-use.

Figure 3-1 6R concept for a near perpetual material flow in a closed-loop

(Jawahir et al., 2006)

3.1.1 Terminologies and Descriptions

A definition of each terminology for the proposed 6R methodology is given in Table 3-1 (ISM, 2012). It is followed by explanations/descriptions that are relevant to the study.

Reduce

Each individual or any combined acts of the rest of 6Rs can be considered as Reduce. It involves the whole process throughout the entire life-cycle stages of a manufactured product. It mainly aims to reduce the use of various kinds of materials and resources, and to reduce the generation of wastes and emissions. Special efforts are commonly made to reduce the use of raw (virgin) material at the PM stage, and the wastes disposed to landfill at the PU stage.

Table 3-1 6R definitions

<table>
<tr><th>6R Element</th><th>Description</th><th colspan="3">Application</th></tr>
<tr><td>Reduce</td><td>Focuses on the first 3 stages of product life-cycle – reduced use of resources in Pre-manufacturing; reduced use of energy and materials during Manufacturing; reduced waste in Use.</td><td>Lean Manufacturing</td><td rowspan="3">Green Manufacturing</td><td rowspan="6">Sustainable Manufacturing</td></tr>
<tr><td>Reuse</td><td>Reuse materials/components/products after its first life--cycle in subsequent life-cycles or other applications, in an effort to reduce the use of new raw materials to produce such materials/components/products.</td><td></td></tr>
<tr><td>Recycle</td><td>Process of converting end-of-life materials (that would otherwise be considered waste) into new material/product for use in new products. Recycling is called for when reuse options are not possible.</td><td></td></tr>
<tr><td>Recover</td><td>Process of collecting materials from end-of-life products, disassembling assembled products, sorting and cleaning for utilization in subsequent life-cycles of the product or for use in other products. Recovery is aimed at reduced recycling.</td><td></td><td></td></tr>
<tr><td>Redesign</td><td>Act of redesigning improved products for manufacture with reduced and/or more efficient/effective resources, and redesigning next generation products by utilizing recovered materials from the end-of-life products from the earlier generation.</td><td></td><td></td></tr>
<tr><td>Re-manufacture</td><td>Reprocessing of end-of-life components/products for restoration to their original state to perform a similar or improved functionality. It involves redesigning of new products utilizing such end-of-life components/products.</td><td></td><td></td></tr>
</table>

Recover

Product recovery can be performed at different levels: at a higher level where components are reused, remanufactured; at a lower level where material recycling is often the outcome. Product recovery leads to the processes for reuse, remanufacturing, and recycling, and involves operations such as disassembly, sorting, shredding, smelting, and refining. It aims to retrieve a product's inherent value at its EOL. It promotes multiple uses of the material, it also extends single lifetime of a product to multiple life spans.

Reuse

A useable and functional component is disassembled from the products for the purpose of either further utilizing them as a product, or as a component to make the same new products or different product assemblies. Some critical processes are typically involved, such as preliminary inspection, precise inspection, and cleaning.

Remanufacture

A worn out/broken/used product is to be restored to its original specifications by means of remanufacturing. The worn out/used product can also be modified and upgraded with new specifications by redesigning the EOL product into a new product. The remanufactured product will then become such a functional unit that preserves equivalent and sometimes even superior features in terms of quality and functionality, reliability and performance, lifetime and appearance. It should also at least endure another full life-cycle.

Recycle

Recycling refers to the process of converting EOL products into new materials; otherwise, these materials would be destined for disposal, if they are not recyclable. Subsequently, recycled materials are to be used in the form of raw materials to make either the same or different new products. Recycling can also be applied to recover energy from EOL products.

Redesign

The purpose of redesign is to produce improved next generation products with the use of recovered materials or components from the earlier EOL generations. It can be for the same products, or for totally different products. The newly redesigned products should show superior features and performance compared with the older generations. Moreover, their related processes of across the entire life-cycle should consume less resources and generate fewer wastes.

3.1.2 The 6R Decision Flow

Figure 3-2 shows the decision flow proposed for metallic automotive components. The virgin materials come into the PM stage, where they are formed to become chunk pieces. The components produced at the M stage go through its U stage, and they finally reach the PU stage, where decisions for various 6R strategic options can be made.

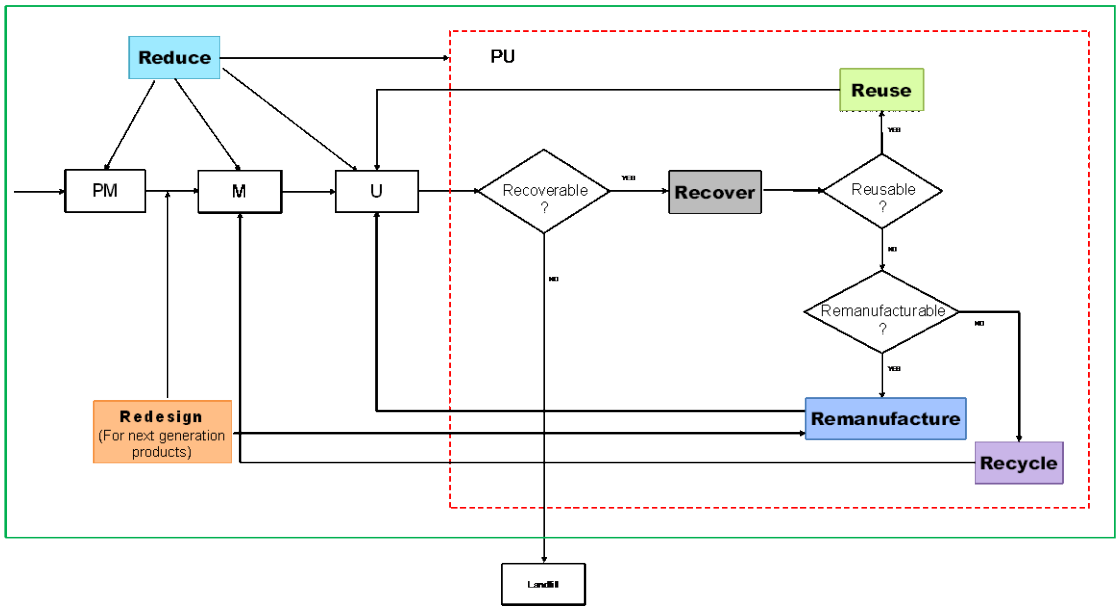

Figure 3-2 The 6R decision flow diagram across four life-cycle stages of metallic automotive components

When the valuable life of metallic automotive components ends at the U stage, if the material cannot be recovered for use as either material or as for energy, then it goes to landfill. If the EOL products are recoverable, otherwise, the first activity to consider is the reuse. After a preliminary inspection and a full cleaning, components eligible for reuse can be directly used for assembly to become new products. If the components are not qualified for reuse, remanufacture is the next activity to consider. If the components do not have serious defects such as damaging cracks, and if their original specifications can be restored by remanufacturing, they can be transported to the manufacturing plant after the material deposition process. If the components suffer from serious damages that they cannot be retrieved to their original specifications by means of remanufacturing, then material recycling will be an alternative practice. After a sequence of recycling processes such as sorting and shredding, the material can be recovered and reused as raw materials to make either the same or different products.

If materials of the components are recoverable, either materials or the components could be reused within a closed-loop. Consequently, virgin materials would be no longer

needed to produce the next generation products as an ideal situation. A closed-loop material flow could be ultimately achieved with the application of 6R methodology.

3.2 Product Sustainability Metrics and the Product Sustainability Index (*ProdSI*) Methodology

3.2.1 Product Sustainability Metrics

The elements/sub-elements of product design for sustainability shown in Figure 3-3 from a early work, serves as a foundation to the development for the comprehensive product sustainability metric system.

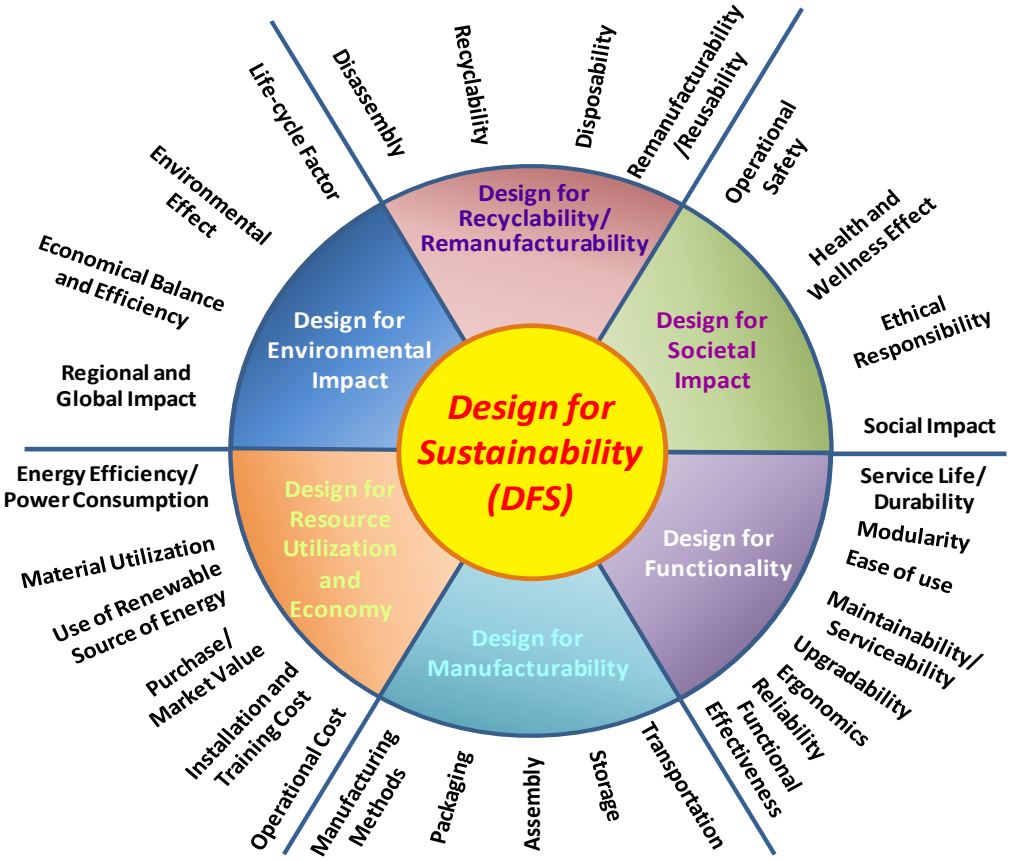

Figure 3-3 Elements/sub-elements of product design for sustainability

(Jawahir et al., 2006)

Each individual metric is generated to measure a specific feature of a product's sustainability. The individual metrics are customizable to fit a specific product to be analyzed or to suit for a family product manufactured in the same industry. More than seventy individual metrics are grouped into sub-clusters according to particular aspects of the product's sustainability. The sub-clusters are then categorized into thirteen (13) different clusters, among which each cluster expresses an element or area of the product sustainability. The clusters are further aggregated with respect to those three major areas of product sustainability - economy, environment, and society, which are named as sub-indices. Finally, these three major aspects are aggregated into the product sustainability index (*ProdSI*). Within the established product sustainability metric system, three (3) clusters are generated for the sub-index Economy, five (5) clusters are developed or each sub-index, Environment and Society. Figure 3-4 shows an overall framework of the *ProdSI* index, its sub-index, and the number of clusters that each sub-index has.

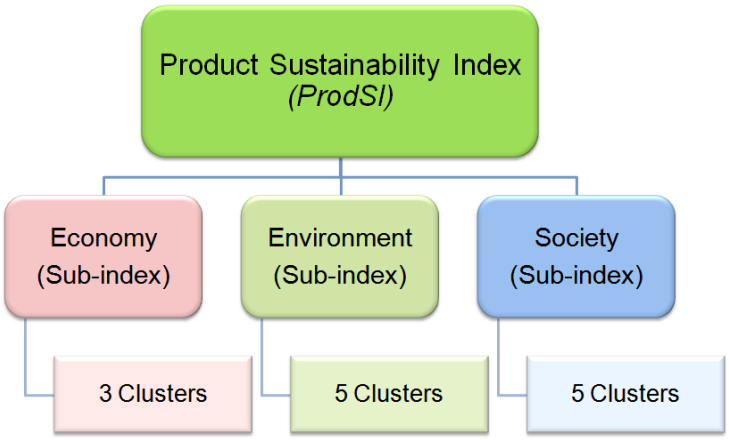

Figure 3-4 The structure of *ProdSI* and its sub-index components with their clusters

Figures 3-5, 3-6, and 3-7 show the identified clusters that for each sub-index, Economy, Environment, and Society (Zhang et al., 2012).

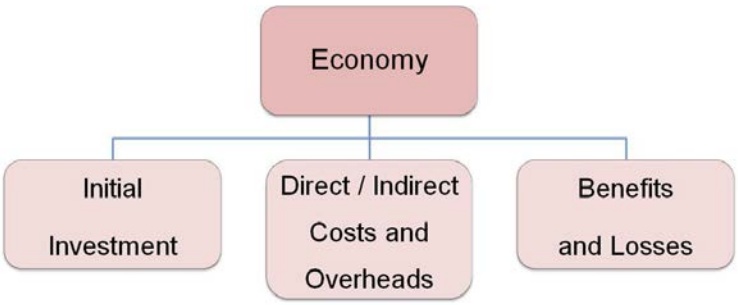

Figure 3-5 Sub-index, Economy, and its clusters

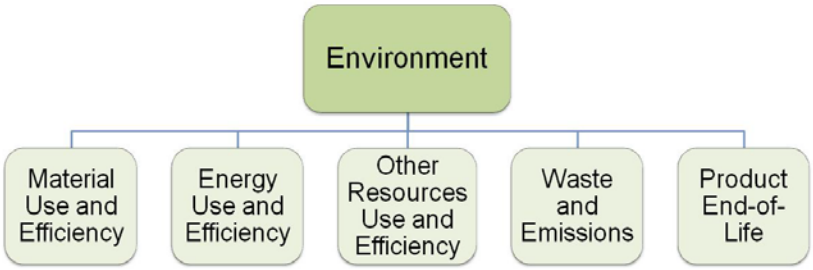

Figure 3-6 Sub-index, Environment, and its clusters

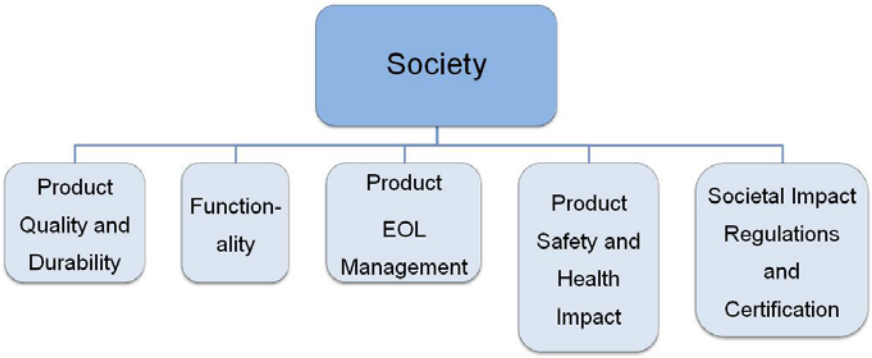

Figure 3-7 Sub-index, Society, and its clusters

The complete set of product sustainability metrics is a large system, it is difficult to show it in a table with all individual metrics. Detailed individual metrics under each sub-cluster are provided in a written form as follows.

For the sub-index of economy, under the cluster of initial investment, the sub-clusters are: capital cost, research and development cost; equipment cost and employee training. Under the cluster of direct/indirect cost and overheads, the sub-clusters are: labor cost; material cost; energy cost; logistics cost; product operational; cost and legal cost. Under the cluster of benefits and losses, the sub-clusters are market value; quality losses.

For the sub-index of environment, under the cluster of material use and efficiency, the sub-clusters are product material content; material utilization; regulations and certification. Under the cluster of energy use and efficiency, the sub-clusters are energy from renewable sources; energy from non-renewable sources; energy regulations and certification; energy efficiency. Under the cluster of other resources use and efficiency, the sub-clusters are: water use; recycled water use; other natural resources; natural resource regulations and certification. Under the cluster of waste and emissions, the sub-clusters are gaseous emissions; solid waste; liquid waste; other waste and emissions; waste management regulations and certification. Under the cluster of product end-of-life (EOL), the sub-clusters are EOL product/material recovery; EOL product reuse, EOL product remanufacturing; EOL recycling, product EOL regulations and certification.

For the sub-index of society, under the cluster of product quality and durability, the sub-clusters are product repair and maintenance, product reliability, return, recall and warranty. Under the cluster of functionality, the sub-clusters are major product specifications, product customizability, product functional effectiveness, ease of operation. Under the cluster of product EOL management, the sub-clusters are ease of disposal, product EOL societal impact. Under the cluster of product safety and health impact, the sub-clusters are safety and health. Under the cluster of product societal impact regulations and certification, the sub-clusters are product EOL regulation compliance, product EOL certification.

3.2.2 Product Sustainability Index (*ProdSI*) Methodology

The product sustainability index is an established comprehensive methodology that assesses sustainability performance of all manufactured products. The *ProdSI* structure is five-leveled and its index value is computed based on the product sustainability metrics introduced from the previous section. The five-level hierarchal configuration includes individual metrics, sub-clusters, clusters, sub-index, and the *ProdSI.* Figure 3-8 shows the five-leveled structure and the assessment methods applied (Zhang et al., 2012).

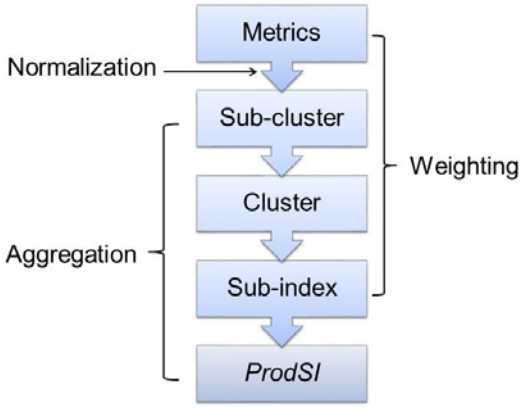

Figure 3-8 The hierarchical structure of the *ProdSI* methodology and the assessment methods applied

By generating the final *ProdSI* score, the overall performance of a particular manufactured product can be obtained, thus ultimately can be analyzed. The generation of *ProdSI* requires a series of procedures - data normalization, weighting, and score aggregation - as shown in Figure 3-9.

Figure 3-9 The five-step hierarchical *ProdSI* evaluation process

Concepts and methodologies applied to each procedure for generating the *ProdSI* are introduced as follows.

The *ProdSI* methodology aims to assess the sustainability content of a product without being limited by a generally accepted practice or certain current technology. When the measured data are to be normalized on to a 0 to 10 scale, the score of 10 representing the best case is assigned only when a theoretically perfect case is achieved. Conversely, a score of zero is given only when the worst conditions occur for a product.

Data Normalization

Physical measurement collected for each individual metric could have inconsistent units so that they cannot be summed up together directly. Even for the same individual measurement, data collected may vary largely due to industrial areas. Therefore, finding a way to compare the performance for each impact category is essential. Normalization allows results of the indicator to be compared by a referenced/controlled value. For the referenced values, quantities for reference region or country during a time period can be usable. For example, the overall emission of CO_2 in the US for a year, and the CO_2-equivalents per capita in Europe per year. As a result, by dividing the reference values, normalized scores become non-dimensional quantities that allow comparisons between different impact categories, even though normalization approaches vary among different impact assessment methods. Physical units are avoided after normalization. Normalization reveals the effects that are large or small in relative terms. It does not tell comparative importance of these effects.

The normalization method developed reflects the physical data on a 0 to 10 scale. Each individual metric is normalized independently. In general, a score of eight and above is assigned to ‘excellent’ status, a score of 6 represents ‘good’ condition, a score of 4 means ‘average’, and a core of 2 and below shows an ‘unacceptable’ stage that needs efforts for an improvement. Normalization scores can be generated according to following scenarios.

Objective Normalization

Regulation and/or standard-guided scenario

Established regulations and standards usually set a single allowable value according to the impact of the subject to be measured. In addition, the overall physical range is separated into two segments, (a) regulation- or standards-compliant, and (b) non-compliant. Different scaling should be considered for each of the segments. Mass of hazardous material use, for instance, is a good example that belongs to this normalization condition.

Purely best and worst case scenario

When a purely best/worst case scenario is considered, normalization scores are assigned based on seriousness of the impact, for example, product material content and energy consumption.

Subjective Normalization

In some cases, it is difficult to quantify some measurements - such as human health impact and societal impact - because of the lack of understanding of the problem. In such cases, subjective normalization approaches can be applied. In general, normalization scores can be generated from subjective surveys or questionnaires for opinions from industrial experts, customers, academic researchers and/or governmental/non-governmental organizations. Unlike the objective normalizations, subjective normalization scores can be sometimes discrete or stepwise.

Scaling Methods and The Range of Physical Data

Results of the measurements after normalization can be represented via different mathematical curves. A linear relationship between the data of a measurement and its impact can be expressed by a linear scaling curve. The data range should be bounded. Several non-linear scaling curves can be used to address relations that are more complex, for example, exponential growth, exponential decay, or stair-wise curves. The data range for non-linear relations can be unbounded. Different scaling methods can be applied for one measurement, depending on the situation or a certain part of the data range that needs can be taken into consideration.

Weighting

A weighting factor is assigned to each of the normalized scores for the sake of further scaling the results in a sense of seriousness and/or importance. Different impact assessment methods follow their own approaches of assigning weightings.

Three weighting methods are commonly accepted and used: equal weighting, subjective weighting, and weighting followed by analytical approaches. An equal weight is assigned to all measurements within a cluster to assume that all elements are equally important. Equal weighting method can be used when the relative importance of each individual metrics is not sensitive or importance of the metrics is not the focus. Subjective weights, associated with subjective judgment towards a value and the importance of an element, can be drawn from statistics and/or from surveys and questionnaires. Typically, opinions considered can be from engagers, customers, industrial peers, experts, original equipment manufacturers, government officials, and so on. For analytical approaches such as analytic hierarchy process (AHP), problems are decomposed into sub-problems, from which their importance is analyzed separately and the result is compared to one another at a time. Finally, the overall weighting factors are generated according to the comparison. Analytic approach might be relatively more objective than the other two; but it is fairly time-consuming and it needs a lot of work force.

When the *ProdSI* is used to compare the sustainability performance of multiple similar products, the comparison should be based on the same normalization and weighting methods. It should be noted that weighting itself is a subjective step, thus weighting scores may not be used for the case of public comparisons among products, according to ISO standards (ISO14040 2006). Weighting is commonly used in life-cycle assessment and product sustainability evaluation; however, it is the least developed, thus it can be one of the most challenging steps among the impact assessment procedures.

Score Aggregation

A comprehensive sustainability index score can finally be generated based on the normalized data and weighting factors applied. The correlations can be expressed by equation (3-1) (Zhang et al., 2012).

$$ProdSI = \frac{1}{3}(E_c + E_v + S_c) = \frac{1}{3}\left(\sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^c C_i + \sum_{i=9}^{13} w_i^c C_i\right) \quad (3\text{-}1)$$

$$c_m = \sum SC_J w_j^u \forall j$$

$$SC_n = \sum M_k w_k^m \forall j$$

where,

Ec Sub-index score for economic impact

Ev - Sub-index score for environmental impact

So - Sub-index score for societal impact

w_i^c - Weighting factor for the *i*th cluster

w_j^{sc} - Weighting factor for the *j*th sub-cluster

w_k^m - Weighting factor for the *k*th metric

C_m - Score for *m*th cluster. C_1 to C_3 are the clusters in the economy sub-index, C_4 to C_8 are the clusters in the environment sub-index and C_9 to C_{13} are the clusters in the society sub-index.

SC_n - Score for the *n*th sub-cluster

M_k - Score for the *k*th metric

3.3 The LCA Methodology

3.3.1 Description of the Methodology

To realize the goal of minimizing the effects on the environment for the manufactured products, and to explore ways of moving beyond compliance by using pollution prevention strategies and environmental management systems to improve environmental performances, LCA enables the estimation of the cumulative environmental impacts coming from all four life-cycle stages of a product. There are several benefits from applying the LCA approach. Getting the results that cause the least impact to the environment is the most direct outcome from using the LCA. The results can be further used in correlation with other elements, such as product performance and economic issues. LCA results tell the transfer of environmental impacts from one life-cycle stage of the product to another (e.g., material flow from the M stage to the U and the PU stages); or from one media to another (e.g., transferring airborne emissions to hydrous type). By enclosing the impacts throughout the product life-cycle, LCA provides comprehensive aspects of the product or process from the environmental point of view. In other words, it gives a more accurate picture of the true environmental trade-offs in the product and process selection, especially when a comparison between two trivial products is performed. Ultimately, it will not only identify a more sustainable product, but it will also examine the consequences of choosing such a product.

Four basic phases are included in this consequential approach. They are: scope and boundary identification; inventory analysis; impact assessment; and interpretation of evaluated results.

Scope and boundary identification

The product to be studied – metallic automotive components made of steel billets - is identified. The study boundary includes those three major aspects of the product sustainability across the product's entire life-cycle stages.

Inventory analysis

Several steps are included in this process:

- Develop flow diagrams for the process scenarios to be analyzed
- Identify the measurements for input and output metrics selected

  For the environmental performance of the automotive component to be modeled and analyzed, individual matrices are customized. Integrating the LCA approach into the *ProdSI* methodology, measurements for the other two aspects of product sustainability - economy and society – are also included. A set of selective metrics are presented in Table 3-2.

Table 3-2 Individual metrics selected for the study

Index	Sub-index	Cluster	Sub-cluster	Individual Metrics	UoM
Product Sustainability Index (*ProdSI*)	**Economy**	Direct/Indirect costs and overheads	Labor cost	Labor cost	$/unit
			Material cost	Material cost	$/unit
			Energy cost	Energy cost	$/unit
			Water cost	Water cost	$/unit
	Environment	Material use and efficiency	Product material content	Total product material use	Kg/unit
				Recycled material ratio of product	%
				Mass of hazardous material use	Mg/unit
		Energy use and efficiency	Energy use	Electricity use	MJ/unit
		Water use and efficiency	Water use	Water use	Kg/unit
		Waste and emissions	Gaseous emission	Greenhouse Gas emission	Kg/unit
			Solid waste	Mass of waste disposed	Kg/unit
		Product end-of-life.	EOL product reuse	Ratio of EOL product reuse	%
			ROL product remanufacturing	Ratio of EOL product remanufactured	%
			EOL product recovery	Ratio of EOL product recovered	%
			EOL product recycling	Ratio of EOL product recycled	%
	Society	Product quality and durability	Product reliability	Life span	Yrs.
				Failure rate	%
		Product safety and health impact	Safety	Injury rate	#/unit

- Develop a plan for data collection and collect data

  In order to secure the quality and accuracy of data to be used in the study, a few issues should be noted to meet the expectations, which are defining quality goals for the data and identifying data sources and data types.

  For the sake of conducting a complete analysis on four life-cycle stages of the product, LCA product models are built with the environmental data inputs – raw material use, use of energy and resources, wastes and emissions. Values from a case study at an automotive manufacturer are adjusted slightly and used for the M stage. For the PM and PU stages, data parameters are obtained based on industrial practices and process equipment manufacturers. Publically available data for a passenger car are normalized by weight for the U stage. Other corresponding unit costs are based on current local market (e.g., labor cost, material cost, electricity and water prices, etc.). The remaining data, which are for societal impact assessments, are mainly approximate values that are representative for the same industry. Data sources and types referred to include well-established European and US databases, industrial reports, laboratory results, government documents, reports, journal literatures, conference papers, former studies on life-cycle assessment and product sustainability evaluation, equipment and process specifications, and other publicly available resources. Therefore, the data used are high in quality and data sources are reliable and trustworthy.

Impact assessment

The objectives in this phase are two folds: to show the improvements of the overall product sustainability by the application of the 6R methodology; and to analyze and evaluate of economic burdens, ecological effects, and human health and safety related issues caused by environmental resources inputs. The impact analysis helps to establish linkages among product life-cycle stages. It builds correlation among those three aspects of the TBL.

Interpretation of evaluated results

After the results are obtained, it is essential to interpret them for transparency. Two major objectives are defined in this step, one of which is to analyze the results, draw conclusions, and address limitations and challenges, and to provide recommendations according to the results gained from the previous step. The other goal is to present the complete and consistent result outcomes, in accordance with the scope and boundary of the case. Two key steps are included:

(a) Compare alternative product EOL strategies

By comparing alternatives, the most potentially sustainable product prototype can be selected for developing the next product generations, when the LCA, in conjunction with the *ProdSI* evaluation, is integrated into product design.

(b) Draw conclusions, limitations and challenges, recommendations, and to present a report.

3.3.2 Most Commonly Used LCA Methods

Some of the most commonly used LCA methods are listed in Table 3-3. Descriptions for each method are given below. In this research study, SimaPro 7.3 software is used, and Eco-indicator 99 (H) is applied as the default assessment method for LCA.

Table 3-3 Commonly used LCA impact assessment methods and tools

Region	Method	Region	Method
European	CML Baseline 2000	North American	EDIP 2003
	Eco-indicator 99 (E/H/I)		EPD 2008
	Impact 2002 +		TRACT (USA EPA)
	ReCiPe Midpoint (E/H/I/E)		BEES (NIST)
	EPS 2000		

Eco-indicator 99

Developed by PRé Consultants B.V., Eco-indicator 99 (Eco-indicator, 1999) is a life-cycle impact assessment tool that helps designers to evaluate a product's environmental impacts by computing eco-indicator scores for materials and processes used. The resulting scores provide indication to the areas of strength and weaknesses of that product. The Eco-Indicator impact assessment is carried out via three sections: production of raw materials, manufacturing processes; transportation of product, energy use, and consumables used for repair and maintenance; and final disposal. The method is damage-oriented that the weighted damage impacts include human health, ecosystem quality, and resources. It goes through three phases before the final score aggregation. The first phase is to calculate resources used, land used, and emissions as an inventory. The second phase is to model and to analyze damages to human health and to ecosystem caused by the usage. Finally, weak area(s) are assessed, thus improvements are indicated by use of weightings (Eco-indicator, 2000).

EPS 2000

EPS 2000 is a systematic approach to Environmental Priority Strategies (EPS). It is also considered as the default methodology for EPS in the stage of product design. The EPS system is primarily used as a tool for a company's internal product development. Its assessments include characterization, damage assessment and evaluation. The impact categories are identified from five areas - human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values. (Steen, 1999)

CML 2 Baseline 2000

The CML 2 baseline is a problem-oriented approach that their indicators are categorized at a mid-point level. Based on the principle of best available practice, a baseline indicator is selected if several methods are available for obligatory impact. It is a simplified method for impact assessment. Therefore, for detailed and extended studies, it provides guidelines for inclusion of other methods and impact category indicators (CMLCA 2001).

Impact 2002 +

The life-cycle impact assessment methodology IMPACT 2002+ is mainly a combination approach that interrelates all life-cycle inventory results among IMPACT 2002, Eco-indicator 99, CML 2000, It considers several midpoint categories, including human toxicity carcinogenic effects, human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic acidification, terrestrial acidification/nitrification, land occupation, turbined water, global warming, non-renewable energy consumption, mineral extraction, water withdrawal and water consumption. All midpoint scores are grouped into four damage categories: human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint level or at damage level. The IMPACT 2002+ methodology provides characterization, damage assessment, normalization and evaluation (Jolliet et al., 2003).

ReCiPe Midpoint

The *ReCiPe* is another midpoint method that primarily transforms the long list of life-cycle inventory results into a limited number of, and easy to understand, indicator scores. These indicator scores express the relative severity on an environmental impact category. Two levels of indicators are determined within *ReCiPe:* eighteen (18) midpoint indicators; and three (3) endpoint indicators. By having these two-level indicator system, it allows the users to choose the certain level results they would like to have. Certain level of damages created by combination of a series of environmental effects can be of threat to human health or ecosystems. Its impact assessments include damages to human health, ecosystem, and resource availability (Goedkoop et al., 2009).

TRACI (US EPA)

Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (*TRACI),* developed by EPA, is aimed at achieving long-term environmental results by assessing the impact for a consistent set of metrics and decision-making framework. It examines the potential impacts associated with the raw material usage and chemical releases from the processes of producing a product. *TRACI* enables the examination of potential impacts for not only a single life-cycle stage, but also the entire life-cycle stages; and further comparison of results between products or processes. Based on available impact categories - ecosystem analysis, human health impact, and resource, energy and land usage, this method can preliminarily determine or to compare among multiple options. Results from the impact assessments are valuable for product life-cycle assessment, industrial ecology, process design, and pollution prevention. This methodology was specifically developed for the input parameters in the United States. Its modular design has the capability of using various simulations to determine the most appropriate characterization factors to represent the various conditions. (*TRACI*, (EPA))

BEES (NIST)

Developed by the National Institute of Standards and Technology (NIST) Engineering Laboratory, the *BEES* (Building for Environmental and Economic Sustainability) is a powerful tool that helps to select cost-effective and environmentally preferable building products. The software is developed and designed based on consensus standards. For evaluating the environmental performance of building products, the LCA approach specified in the ISO 14040 is applied. All stages in the life-cycle of a product are analyzed: raw material acquisition, manufacturing, transportation, installation, use, and recycling as well as waste management. For measuring the economic performance of products, LCC method that is standardized in the standard system of American Society for Testing and Materials (ASTM) is used. The measurements cover the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Finally, environmental and economic performance evaluated is combined into an overall performance analysis (*BEES*, Descripion/Summary).

3.4 Summary

A new methodology was presented in this chapter for assessing the sustainability performance of metallic automotive components. Based on the comprehensive metrics for the product sustainability, the sustainability performance of a manufactured product can be comprehensively evaluated via using the *ProdSI* methodology. The 6R methodology can be applied throughout the entire life-cycle of the product. Improvements of the overall sustainability can be achieved with the use of the 6R methodology. The improvements can be quantitatively assessed by calculating the *ProdSI* score.

In the next chapter, the proposed methodology will be demonstrates systematically via modeling of the total life-cycle stages for metallic automotive components.

CHAPTER 4

LIFE-CYCLE MODELING OF METALLIC AUTOMOTIVE COMPONENTS AND MATHEMATICAL MODEL FOR PRODUCT SUSTAINABILITY METRICS

In this chapter, the new methodology discussed in the previous chapter is demonstrated. LCA models for metallic automotive components are built with the consideration of total life-cycle of the product. Different product EOL scenarios are analyzed. As a result of applying the 6R methodology, the overall product sustainability shows improvements. The first part of this chapter presents the modeling work and the results for various product EOL scenarios. The second part of this chapter presents a mathematical model that aims to find an optimum percentage mix for the product EOL activities. An ultimate closed-loop material flow can be achieved.

According to the 6R methodology, reduce and recovery are involved throughout the entire life-cycle stages of a product. Reduce focuses on reducing the use of raw materials and resources, and reducing wastes and emission. Product recovery includes the processes that are aimed at promoting the reuse of materials/components, such as EOL product collection, sorting, and cleaning. The recovered materials/components are further utilized in the subsequent life-cycle of the same or other products. Therefore, emphasizing the EOL product reuse, remanufacturing, and recycling becomes the focus of the section for modeling the product's life-cycle. Quantities of the selected metrics (mass of hazardous material use, energy use, water use, greenhouse gas emission, and mass of waste disposed) are expected to change, regardless of whether the EOL components are reused, remanufactured, or whether the EOL components are recovered through material recycling.

Several assumptions are made for the LCA product models.

- The chosen product is a stand-alone manufactured component from a single material.

- It is assumed that all outputs of 6R activities within this research are used for producing the same components, not for other products.

- Because the components are made of alloy steel, the percentage of component reused, remanufactured, and the percentage of material recycled are assumed to be unanimous with the ratio of reused, remanufactured, and recycled EOL product respectively.

To analyze the effects of applying different EOL activities on the sustainability behavior of the chosen product, four life-cycle stages of the product are modeled in SimaPro. Data received from a case study at an automotive manufacturer are adjusted slightly and used for the M stage. Values for the U stage are normalized per weight of a vehicle. Input parameters obtained based on the industrial practices and process equipment manufacturers for the PM and PU stages are provided in Table 4-1.

Table 4-1 Input parameters to the LCA software

Inventory Categories		Inputs (per component)		Amount	Unit
Materials	Metal	Metallic automotive component raw piece		26.55	Kg
			Steel, billet, at plant/US	26.55	Kg
			Induction heating	26.55	Kg
			Press hammering	26.55	Kg
			Truck 16t	0.13	tkm
		Metallic automotive component finished product		21.92	Kg
			Metallic automotive component raw piece	26.55	Kg
			Water, unspecified natural origin, US (in ground)	10.41	Kg
			Electricity, production mix US/US U	58.82	Kg
			Truck 16t	0.13	tkm
			Metallic automotive component chips recycling	4.63	Kg
Processing	Chipless Shaping	Induction heating (Induction billet heater)		26.55	Kg
			Water, unspecified natural origin, US (in ground)	533.20	L
			Electricity, production mix US/US U	44.00	kWh
		Press hammering (Forging press hammer)		26.55	Kg
			Electricity, production mix US/US U	6.68	kWh
		Metallic automotive component smelting (Smelter)		21.92	Kg
			Water, unspecified natural origin, US (in ground)	394.56	L
			Electricity, production mix US/US U	13.59	kWh

Inventory Categories		Inputs (per component)		Amount	Unit
Processing	Chipping	Metallic automotive component shredding (Shredder)		21.92	Kg
			Electricity, production mix US/US U	1.21	kWh
	Coating	Metallic automotive component plasma thermal powder coating, steel/RER U		4.63	Kg
			Water, unspecified natural origin, US (in ground)	617.28	L
			Electricity, production mix US/US U	67.52	kWh
			Steel powder, billets, at plant/US	4.63	Kg
	Others	Metallic automotive component magnetic particle inspection		21.92	Kg
			Electricity, production mix US/US U	1.00	kWh
		Metallic automotive component steam spray cleaning (Steam spray cleaning system)		21.92	Kg
			Water, unspecified natural origin, US (in ground)	208.20	L
			Electricity, production mix US/US U	1.50	kWh
	Transport	Truck 16t		0.0430	tkm
		Truck 16t		0.1300	tkm
		Truck 16t		0.0081	tkm
		Metallic automotive component sorting (Material handler excavator)		21.9200	Kg
			Electricity, production mix US/US U	0.0008	kWh

Inventory Categories		Inputs (per component)		Amount	Unit
Processing	Waste Treatment	Metallic automotive component chips disposal, steel, to inert material landfill/Kg/CH		4.63	Kg
			Steel waste	4.63	Kg
			Truck 16t	0.0081	tkm
		Metallic automotive component disposal, steel, to inert material landfill/Kg/CH		21.92	Kg
			Steel waste	21.92	Kg
			Truck 16t	0.0430	tkm
		Metallic automotive chips recycling		4.63	Kg
			Steel, billet, at plant/US	4.58	Kg
			Truck 16t	0.0081	tkm
			Slags and ashes	0.0463	Kg
	Waste Treatment	Metallic automotive recycling		21.92	Kg
			Steel, billet, at plant/US	21.70	Kg
			Truck 16t	0.0430	tkm
			Slags and ashes	0.2200	Kg
			Metallic automotive component sorting	21.92	Kg
			Metallic automotive component shredding	21.92	Kg
			Metallic automotive component smelting	21.92	Kg

4.1 Life-Cycle Modeling of Metallic Automotive Components

4.1.1 Modeling the Reused EOL Product

4.1.1.1 Description

Figure 4-1 illustrates the decision flow for reusing the products at their EOL. Figure 4-2 shows all involved processes for reusing EOL products across four life-cycle stages.

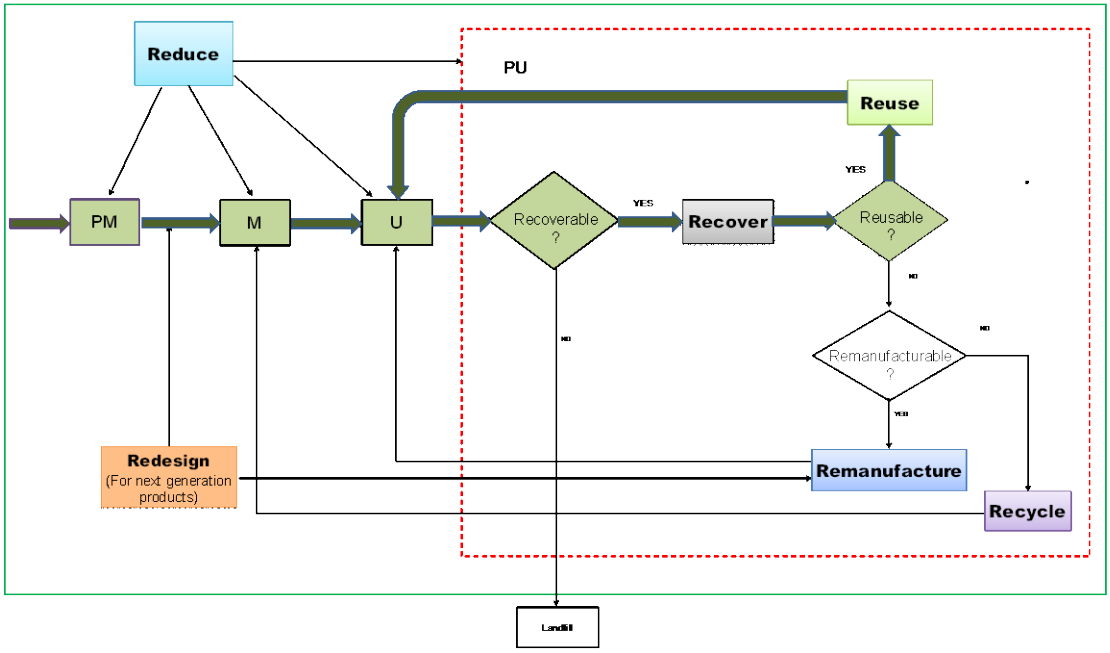

Figure 4-1 Decision flow diagram across four life-cycle stages for reusing EOL products

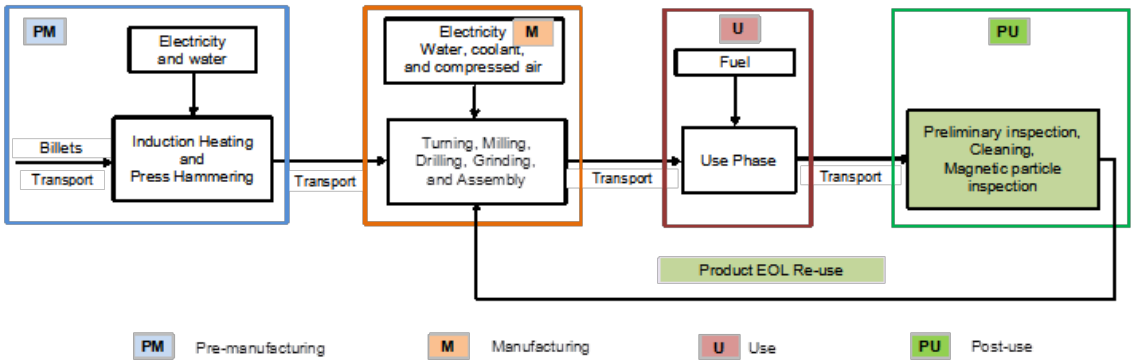

Figure 4-2 Process map across four life-cycle stages for reusing EOL products

The processes considered for the PM stage include induction heating and press hammering. The same processes are considered for the PM stage of the other two EOL product scenarios: EOL product remanufacturing and recycling.

The processes for producing finished products in the M stage involve turning, milling, drilling, and grinding. The same manufacturing plant is considered for the scenarios of remanufacturing and recycling the EOL products.

In the U stage, input parameters are normalized by weight of a car.

In the PU stage, since the components are made of alloy steel which can be fully recovered, they go through a series of EOL processes including a preliminary inspection, EOL product cleaning, and a precise inspection. For the components that pass the magnetic particle inspection, they can be directly used to make new products.

4.1.1.2 Results and analysis

Mass of Hazardous Material Use

Table 4-2 shows the changes of mass of hazardous material use when the ratio of reused EOL product varies from 0% to 90%. In the PM and M stages, the mass of hazardous material use decreases linearly as an effect of fewer virgin materials used.

Table 4-2 Mass of hazardous material use for various ratio of reused EOL product

% Re-use	Mass of hazardous material use (mg/unit)				
	PM	M	U	PU	Total
0%	120.20	40,000	0.00	0.00	40,120.20
20%	96.20	32,000	0.00	18.21	32,114.41
40%	72.10	24,000	0.00	17.67	24,089.77
60%	48.20	16,000	0.00	17.03	16,065.23
80%	24.16	8,000	0.00	16.39	8,040.55
90%	12.01	4,000	0.00	15.97	4,027.98

In the M stage, the mass of hazardous material use contains mainly used coolant; it also includes other forms of hazardous contents, such as fumes and metal debris. The used coolant is 100% recycled. Value for the U stage stays zero as the components do not generate any hazardous materials during its U stage. Constant trends apply to all subsequent individual metrics for both M and the U stages analyzed in this study. In the PU stage, the amount of hazardous material use increases as the ratio of reused EOL product increases. This is because more product EOL activities are involved along with the increase of reusing old products. This trend can be represented by the curve shown in Figure 4-3, and it can be expressed by Eqn. (4-1), where the mass of hazardous material

use is expressed as a function of the ratio of reused EOL product (x). The function is obtained by fitting a curve to the trend line.

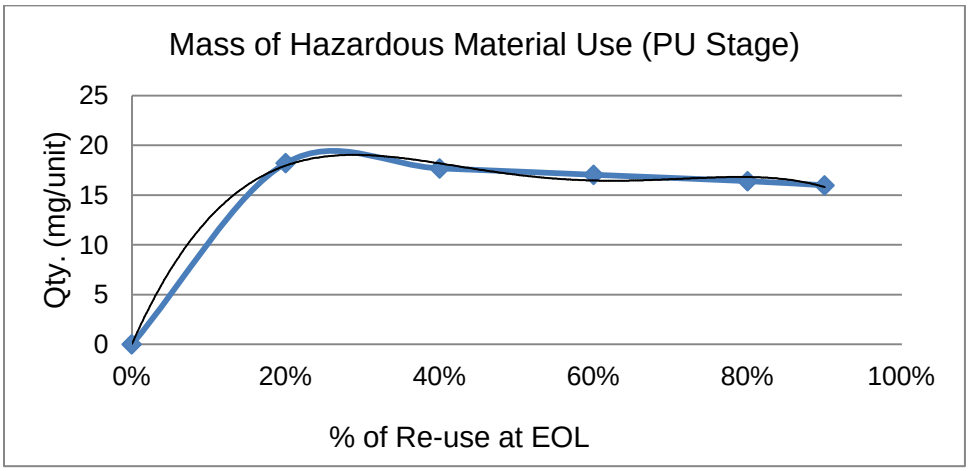

Figure 4-3 Variation curve for mass of hazardous material use at the PU stage of reusing EOL products

$$y_{mh_{pu}} = -306.67\,x^4 + 696.68\text{x}^3 - 553.47\text{x}^2 + 174.88\,x + 0.05 \qquad (4\text{-}1)$$

The total mass of hazardous material use for four life-cycle stages drops linearly when the ratio of reused EOL product varies from 0% to 90%. This decreasing trend can be represented by the curve shown in Figure 4-4; and it can be expressed by Eqn. (4-2).

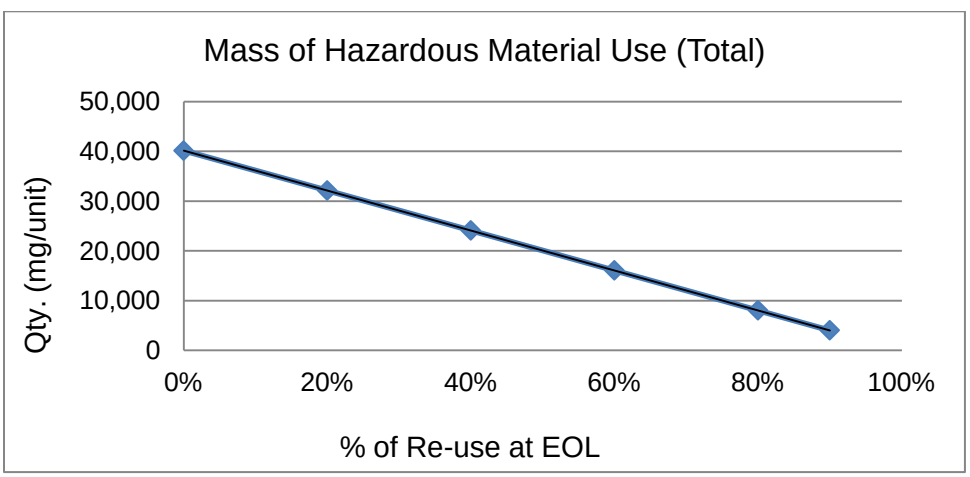

Figure 4-4 Variation curve for total mass of hazardous material use of reusing EOL products

$$y_{mh_{total}} = -40108\,x + 40129 \quad (4\text{-}2)$$

Energy Use

Table 4-3 shows how the energy use changes when the ratio of reused EOL product varies from 0% to 90%. In the PM and the M stages the amount of energy use is a combination for both, due to the fact that less numbers of products are manufactured when some EOL components are reused. Therefore, reduced need for virgin materials results to a decrease in the energy use at these two stages. This trend can be represented by the curve shown in Figure 4-5, and it can be expressed by Eqn. (4-3).

Table 4-3 Energy use for various ratio of reused EOL product

% Re-use	Energy (MJ/unit)			
	PM + M	U	PU	Total
0%	405.00	8,913.56	0.00	9,318.56
20%	366.20	8,913.56	1.80	9,281.56
40%	274.40	8,913.56	3.60	9,191.56
60%	183.60	8,913.56	5.40	9,102.56
80%	91.90	8,913.56	7.20	9,012.66
90%	45.70	8,913.56	8.10	8,967.36

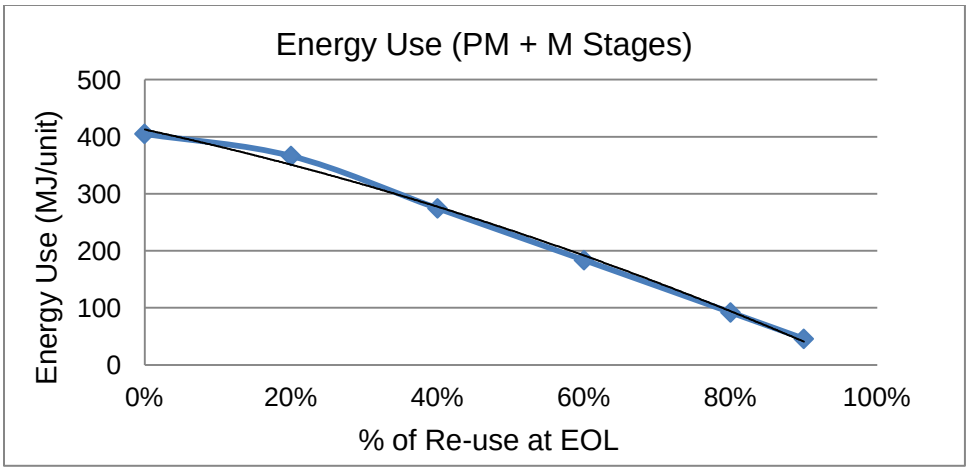

Figure 4-5 Variation curve for energy use at the PM and M stage of reusing EOL products

$$y_{eu_{pm+m}} = -149.4\,x^2 - 278.67\,x + 412.54 \tag{4-3}$$

In the PU stage, the energy use increases linearly when the ratio of reused EOL product increases.

The total energy use for four life-cycle stages decrease as expected when the ratio of reused EOL product varies from 0% to 90%. This decreasing trend can be represented by the curve shown in Figure 4-6, and it can be expressed by Eqn. (4-4).

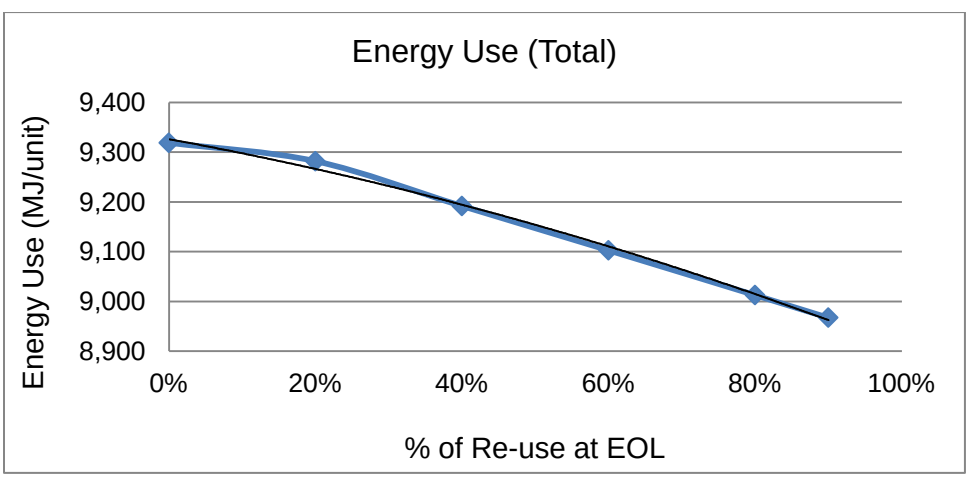

Figure 4-6 Variation curve for total energy use of reusing EOL products

$$y_{eu_{total}} = -149.4\,x^2 - 269.67\,x + 9326.1 \quad (4\text{-}4)$$

Water Use

Table 4-4 shows how water use changes when the ratio of reused EOL product varies from 0% to 90%. In the PM and the M stages, the water use decreases linearly because it is directly related to the amount of virgin materials used.

Table 4-4 Water use for various ratio of reused EOL product

% Re-use	Water (Kg/unit)				
	PM	M	U	PU	Total
0%	616.59	10.41	0.00	0.00	627.00
20%	493.67	8.33	0.00	357.00	859.00
40%	369.75	6.25	0.00	320.00	696.00
60%	246.84	4.16	0.00	283.00	534.00
80%	123.92	2.08	0.00	245.00	371.00
90%	62.60	1.04	0.00	227.00	290.64

In the PU stage, the water use shows a rapid increase as the ratio of reused EOL product increases to 20%. The rapid growth in water use is due to the effect of turning on the entire EOL operating system. And, then it reduces slowly along with the percentage of reusing EOL products changes from 20% to 90%. This trend is shown in Figure 4-7, and it can be expressed by Eqn. (4-5).

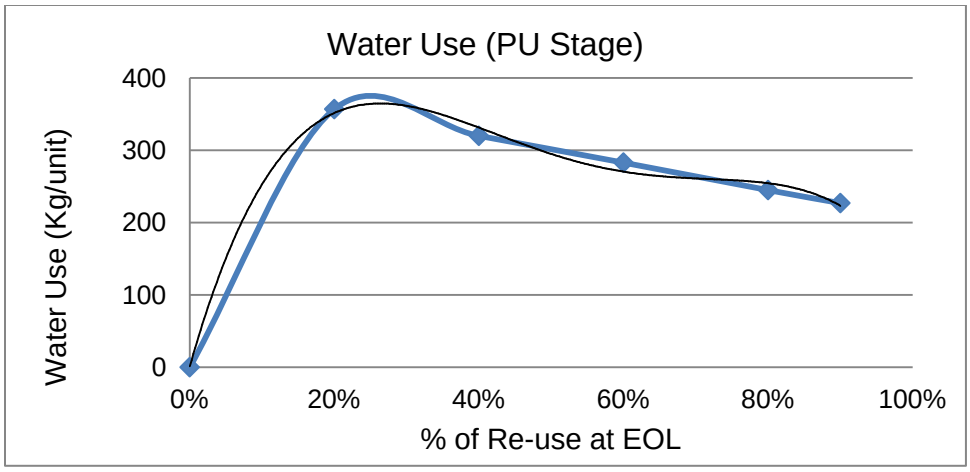

Figure 4-7 Variation curve for water use at the PU stage of reusing EOL products

$$y_{wu_{pu}} = -6370.2\,\mathrm{x}^4 + 14523\,\mathrm{x}^3 - 11566\,x^2 + 3536\,x + 1.05 \quad (4\text{-}5)$$

Total water use for four life-cycle stages increases as the ratio of EOL product recycled increases to 20%, then it drops as the percentage increases to 90%. This trend can be represented by the curve shown in Figure 4-8, and it can be expressed by Eqn. (4-6).

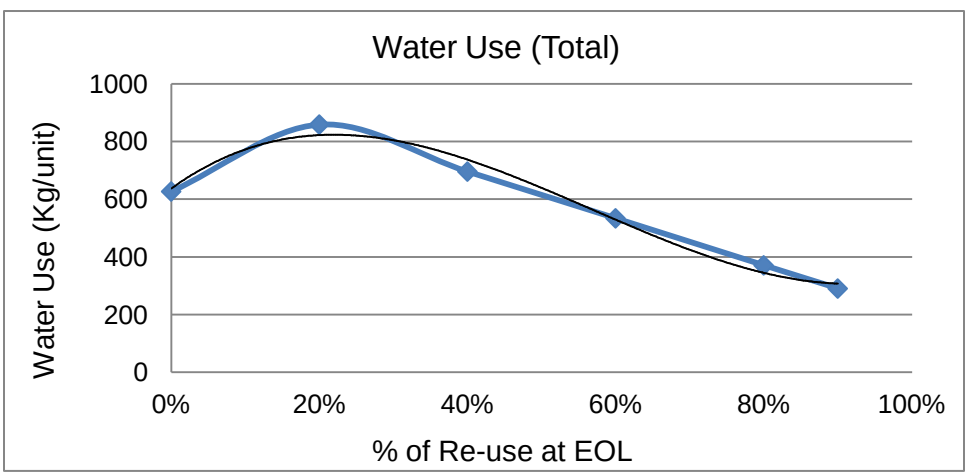

Figure 4-8 Variation curve for total water use of reusing EOL products

$$y_{wu_{total}} = 3061.7\,\mathrm{x}^3 - 5210.9\,x^2 + 1843.1\,x + 637.52 \quad (4\text{-}6)$$

Greenhouse Gas Emissions

Table 4-5 shows the changes of Greenhouse Gas emission when the ratio of reused EOL product varies from 0% to 90%. In the PM and the M stages, the Greenhouse Gas emissions decrease linearly due to the decreasing amount of virgin material used.

It can be observed that the major contribution of the GHG emission comes from the U stage, because a vehicle consumes a large quantity of energy.

Table 4-5 Greenhouse Gas emission for various ratio of reused EOL product

% Re-use	Greenhouse Gas emission (Kg/unit)				
	PM	M	U	PU	Total
0%	55.52	52.35	278,370.71	0.00	278,478.58
20%	44.50	41.88	278,370.71	0.33	278,457.42
40%	33.25	31.41	278,370.71	0.27	278,435.64
60%	22.17	20.94	278,370.71	0.21	278,414.03
80%	11.09	10.47	278,370.71	0.14	278,392.41
90%	5.53	5.24	278,370.71	0.11	278,381.59

The Greenhouse Gas emissions in the PU stage shows a rapid increase when the ratio of reused EOL product increases to 20%, then it drops slowly when the percentage of reusing EOL products changes from 20% to 90%. This trend can be represented by the curve shown in Figure 4-9, and it can be expressed by Eqn. (4-7).

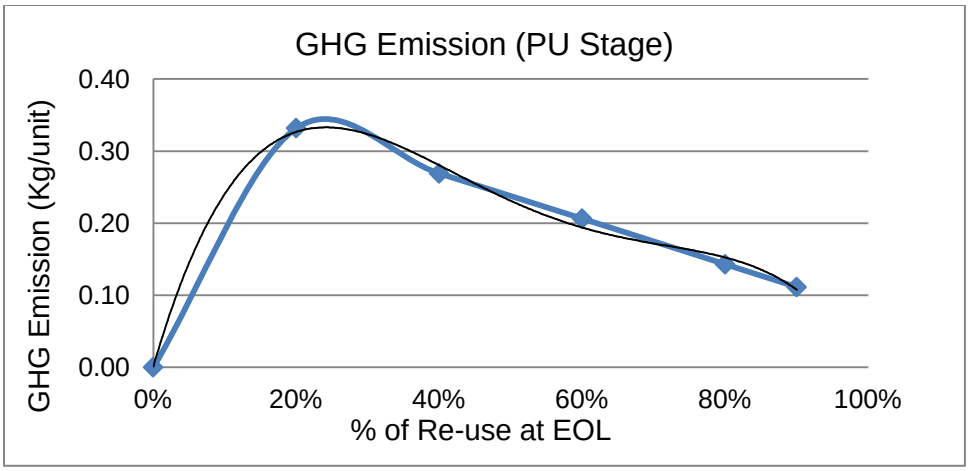

Figure 4-9 Variation curve for GHG emission at the PU stage of reusing EOL products

$$y_{ge_{pu}} = -6.43\,x^4 + 14.63\text{x}^3 - 11.63\text{x}^2 + 3.42 \quad (4\text{-}7)$$

The total Greenhouse Gas emission for four life-cycle stages shows a linear decrease as shown in Figure 4-10, and it can be expressed by Eqn. (4-8).

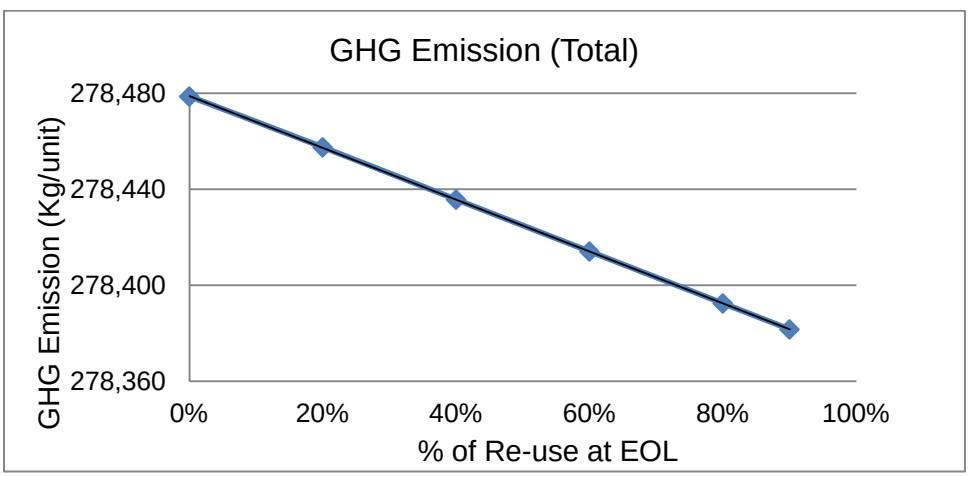

Figure 4-10 Variation curve for total GHG emission of reusing EOL products

$$y_{ge_{total}} = -107.93\,x + 278479 \quad (4\text{-}8)$$

Direct Cost

Table 4-6 Cost data used in this study

Item	Unit Price
Labor cost	$ 15/hour
Material cost	$ 2.12/Kg
Electricity cost	$ 0.0505/kWh
Water cost	$ 1.52/ton

Table 4-6 provides the cost data that are used to calculate all cost related metrics in this study. For the labor cost, it is directly proportional to the hours of workforce involved in the processes at each product life-cycle stage. Its values of variation are shown in Table 4-7. All the other economic metrics selected – material cost, energy cost, and water cost - are directly related to the amount of usage for each metric. Tables 4-8, 4-9, and 4-10 show variations of material, energy, and water costs, respectively. It can be observed that the material cost, energy cost and water cost all show a decreasing trend as a result of reducing the use of virgin materials; while only the labor cost increases. This is because more labor hours are involved at the PU stage when the percentage of reused EOL product increases.

Table 4-7 Labor cost for various ratio of reused EOL product

% Re-use	Labor cost ($/unit)				
	PM	M	U	PU	Total
0%	3.33	3.59	0.00	0.00	6.92
20%	2.67	2.87	0.00	3.38	8.92
40%	2.00	2.15	0.00	6.75	10.90
60%	1.33	1.43	0.00	10.13	12.89
80%	0.67	0.72	0.00	13.50	14.89
90%	0.33	0.36	0.00	15.19	15.88

Table 4-8 Material cost for various ratio of reused EOL product

% Re-use	Material cost ($/unit)				
	PM	M	U	PU	Total
0%	45.00				45.00
20%	36.00				36.00
40%	27.00				27.00
60%	18.00				18.00
80%	9.00				9.00
90%	4.50				4.50

Table 4-9 Energy cost for various ratio of reused EOL product

% Re-use	Energy cost ($/unit)			
	PM & M	U	PU	Total
0%	5.68	125.04	0.00	130.72
20%	5.14	125.04	0.03	130.21
40%	3.85	125.04	0.05	128.94
60%	2.85	125.04	0.08	127.97
80%	1.29	125.04	0.10	126.43
90%	0.64	125.04	0.11	125.79

Table 4-10 Water cost for various ratio of reused EOL product

% Re-use	Water cost ($/unit)				
	PM	M	U	PU	Total
0%	0.94	0.02	0.00	0.00	0.96
20%	0.75	0.01	0.00	0.54	1.30
40%	0.56	0.01	0.00	0.49	1.06
60%	0.38	0.01	0.00	0.43	0.82
80%	0.19	0.00	0.00	0.37	0.56
90%	0.10	0.00	0.00	0.35	0.45

Total direct cost values can be computed by summing up the costs for each varying ratio of reused EOL product. From the results shown in Table 4-11, a decreasing trend can be observed. This trend can be presented by the linear curve shown in Figure 4-11, and it can be expressed by Eqn. (4-9).

Table 4-11 Total direct cost for various ratio of reused EOL product

% Re-use	Total direct cost ($/unit)
0%	183.60
20%	176.43
40%	167.90
60%	159.68
80%	150.88
90%	146.62

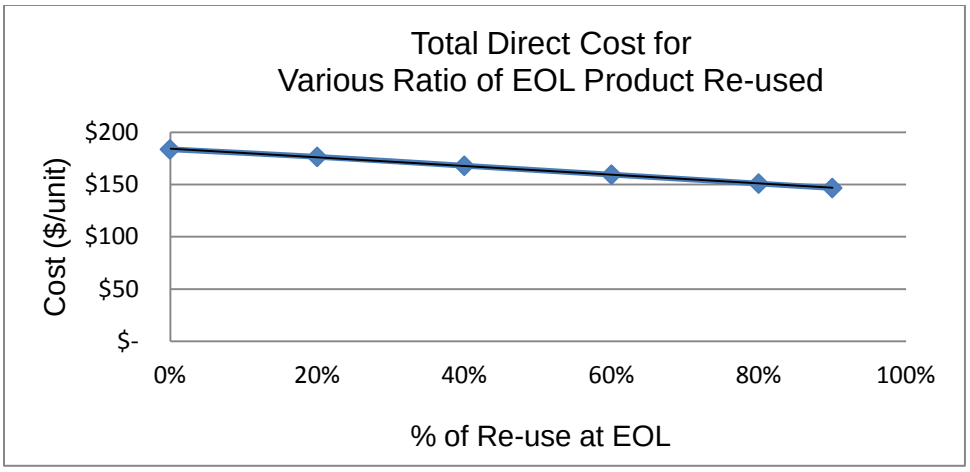

Figure 4-11 Variation curve for the total direct cost of reusing EOL products

$$y_{cost_{total}} = -41.51x + 184.19 \quad (4\text{-}9)$$

4.1.1.3 Comparison of Results and Summary

As a result of reusing EOL products and reducing the amount of virgin materials involved, the selective metrics all show decreases at various degrees.

Producing new products with reused components, compared with using virgin materials, shows improved product sustainability. Most economic, environmental, and societal impacts are directly or indirectly related to the use of virgin materials and resources. As an example, Figure 4-12 illustrates the large difference in the use of hard coal to make new products. The direction of arrows shows where the impact is from. Thickness of the red lines represents the seriousness of the impact. The thicker the red line is, the larger the impact is. Green lines represent how much resources are voided from reusing EOL products. Simply put, the wider the green lines are, the more sustainable the modeled product is. It is apparent that the use of hard coal is a lot less, when 90% of EOL products are reused comparing with the 20% of reusing EOL products.

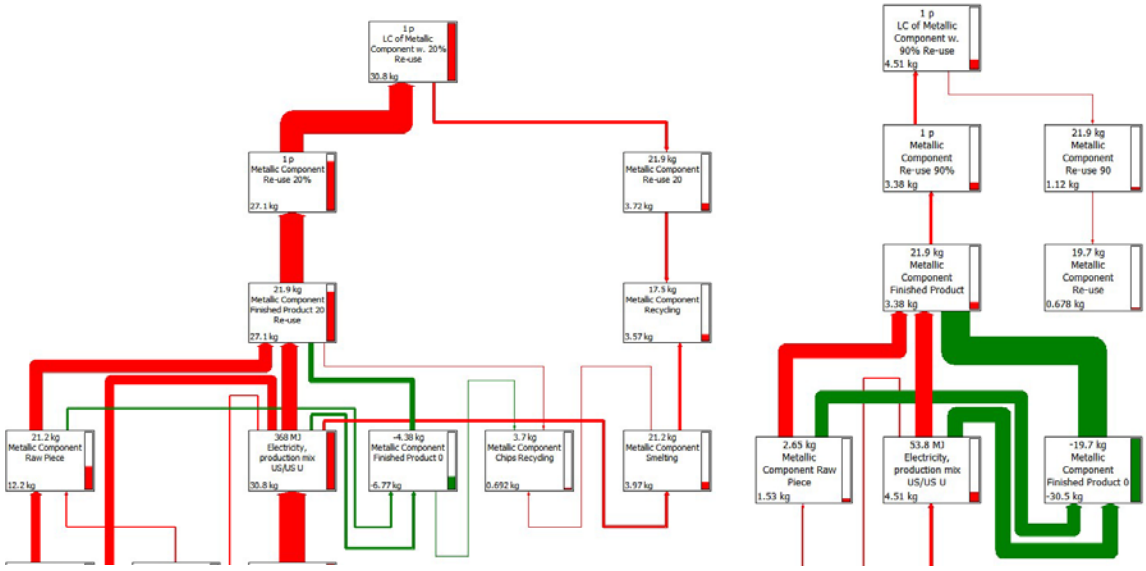

Figure 4-12 Comparison for hard coal use at 20% vs. 90% ratio of reusing EOL product

4.1.2 Modeling the Remanufactured EOL Product

4.1.2.1 Description

Figure 4-13 illustrates the decision flow for remanufacturing the products at their EOL. Figure 4-14 shows all involved processes for remanufacturing EOL products across four life-cycle stages.

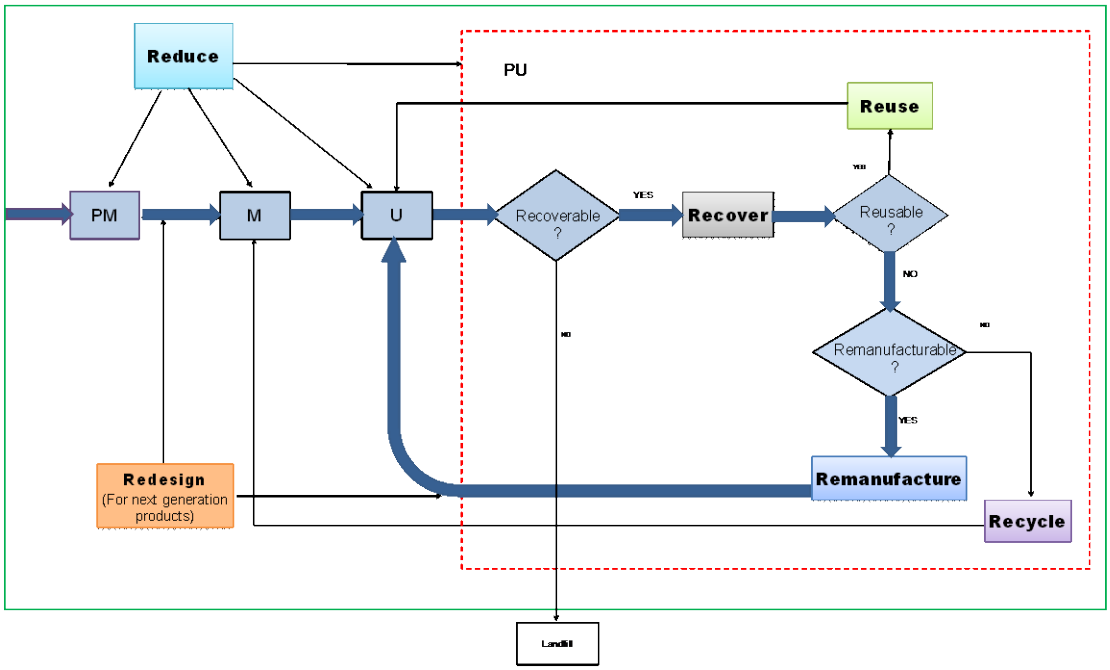

Figure 4-13 Decision flow diagram across four life-cycle stages for remanufacturing EOL products

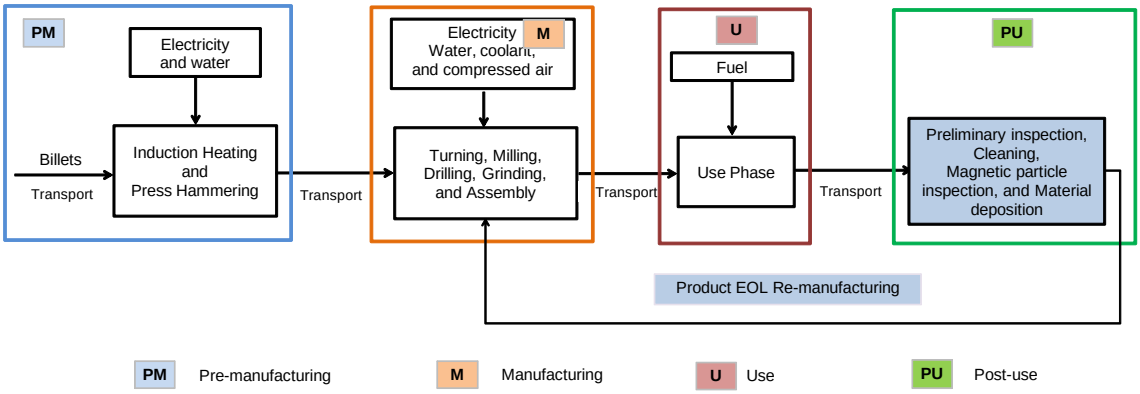

Figure 4-14 Process map across four life-cycle stages for remanufacturing EOL products

In the PU stage, the processes of remanufacturing the EOL components include preliminary inspection, cleaning, magnetic particle inspection, and material deposition. The origin states of the product can be restored from remanufacturing.

4.1.2.2 Results and analysis

Mass of Hazardous Material Use

Table 4-12 shows the changes of mass of hazardous material use when the ratio of remanufactured EOL product varies from 0% to 90%. In the PM and the M stages, the mass of hazardous material use shows a linear decreasing trend as a result of using fewer virgin materials.

Table 4-12 Mass of hazardous use for various ratio of remanufactured EOL product

% Re-manufacturing	Mass of hazardous material use (mg/unit)				
	PM	M	U	PU	Total
0%	120.20	40,000	0.00	0.00	40,120.20
20%	96.20	32,000	0.00	34.90	32,131.10
40%	72.10	24,000	0.00	50.90	24,123.00
60%	48.20	16,000	0.00	66.90	16,115.10
80%	24.16	8,000	0.00	82.80	8,106.96
90%	12.01	4,000	0.00	90.80	4,102.81

In the PU stage, the amount of hazardous material use shows a large increase when the ratio of remanufactured EOL product increases. The slope of increase is larger than the one of the scenario for reusing the old products. This is because one additional EOL process is needed for remanufacturing, which is material deposition for powered steel. This trend can be represented by the curve shown in Figure 4-15, and it can be expressed by linear Eqn. (4-10).

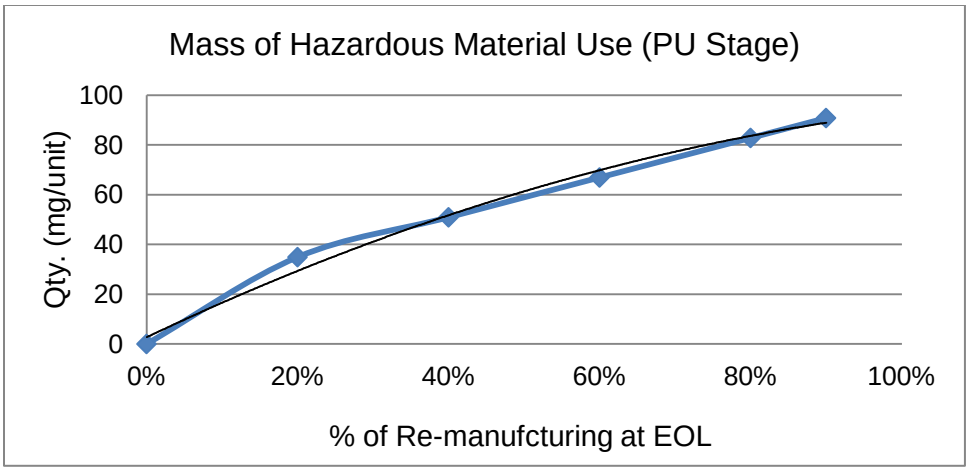

Figure 4-15 Variation curve for mass of hazardous material use at the PU stage of remanufacturing EOL products

$$y_{mh_{pu}} = -53.64\text{x}^2 + 144.05\,x + 2.73 \tag{4-10}$$

The total hazardous material used for four life-cycle stages shows a linear decrease when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be represented by the curve shown in Figure 4-16, and it can be expressed by Eqn. (4-11).

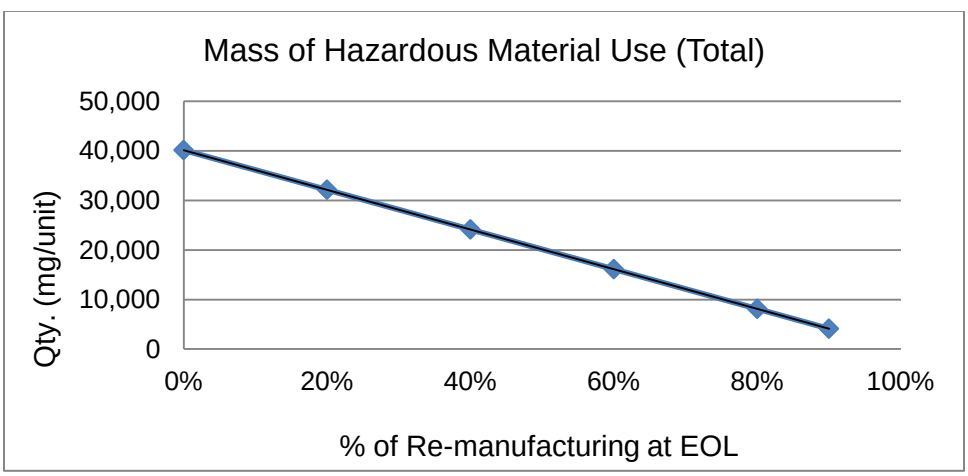

Figure 4-16 Variation curve for total mass of hazardous material use of remanufacturing EOL products

$$y_{mh_{total}} = -40025\,x + 40129 \quad (4\text{-}11)$$

Energy Use

Table 4-13 shows how the energy use changes when the ratio of remanufactured EOL product varies from 0% to 90%. In the PM stage, the energy use shows a decreasing trend, which can represented by the curve shown in Figure 4-17, and it can be expressed by Eqn. (4-12).

Table 4-13 Energy use for various ratio of remanufactured EOL product

% Re-manufacturing	Energy (MJ/unit)				
	PM	M	U	PU	Total
0%	193.25	211.75	8,913.56	0.00	9,318.56
20%	154.60	169.40	8,913.56	274.00	9,511.56
40%	92.76	127.05	8,913.56	519.19	9,652.56
60%	37.10	84.70	8,913.56	757.20	9,792.56
80%	7.42	42.35	8,913.56	970.23	9,933.56
90%	0.74	21.18	8,913.56	1068.08	10,003.56

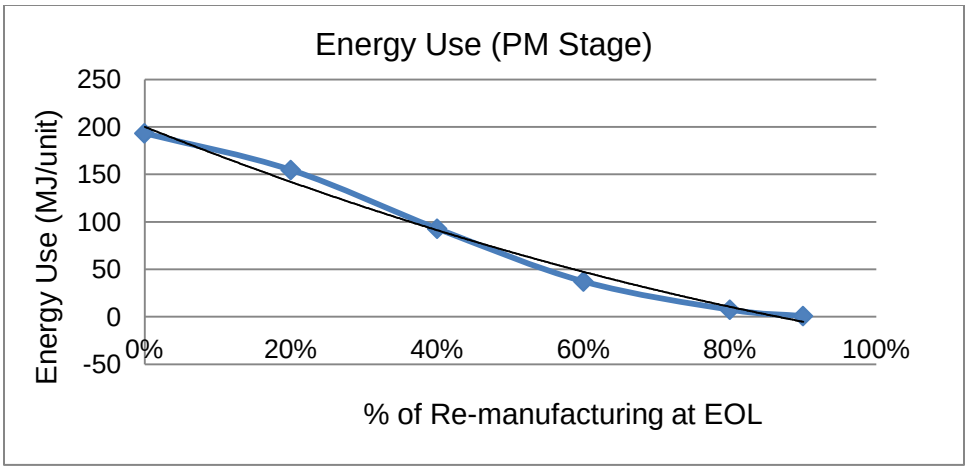

Figure 4-17 Variation curve for energy use at the PM stage of remanufacturing EOL products

$$y_{eu_{pm}} = 88.58\,x^2 - 307.94\,x + 200.14 \tag{4-12}$$

In the M stage, the amount of energy use decreases linearly because fewer virgin materials are involved when EOL products are remanufactured.

In the PU stage, more remanufacturing activities are involved, and this leads to a rapid increase in energy use when the ratio of remanufactured EOL product increases. This is especially due to the process of thermal spray for powered material. This trend can be represented by the curve shown in Figure 4-18, and it can be expressed by Eqn. (4-13).

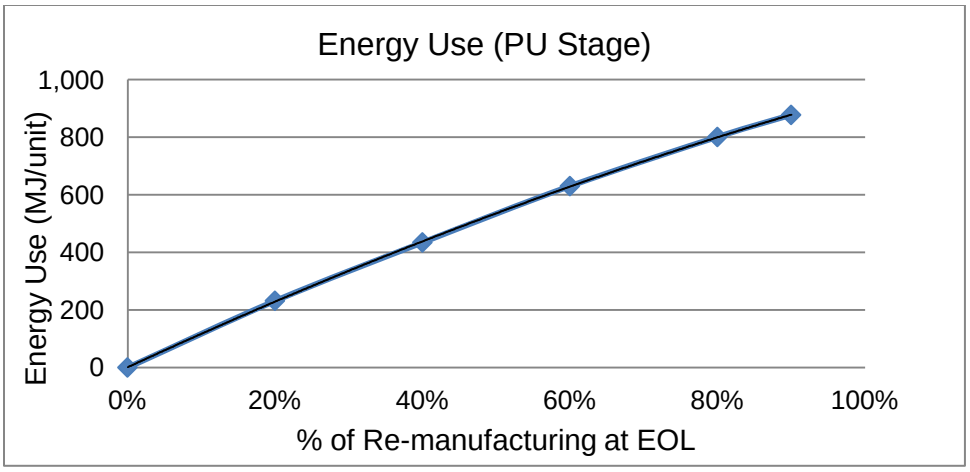

Figure 4-18 Variation curve for energy use at the PU stage of remanufacturing EOL products

$$y_{eu_{pu}} = -237.28\,x^2 + 1188.8\,x + 0.675 \tag{4-13}$$

The total energy use for four life-cycle stages increases tremendously when the ratio of remanufactured EOL product varies from 0% to 90%. This increasing trend can be represented by the curve shown in Figure 4-19, and it can be expressed by Eqn. (4-14).

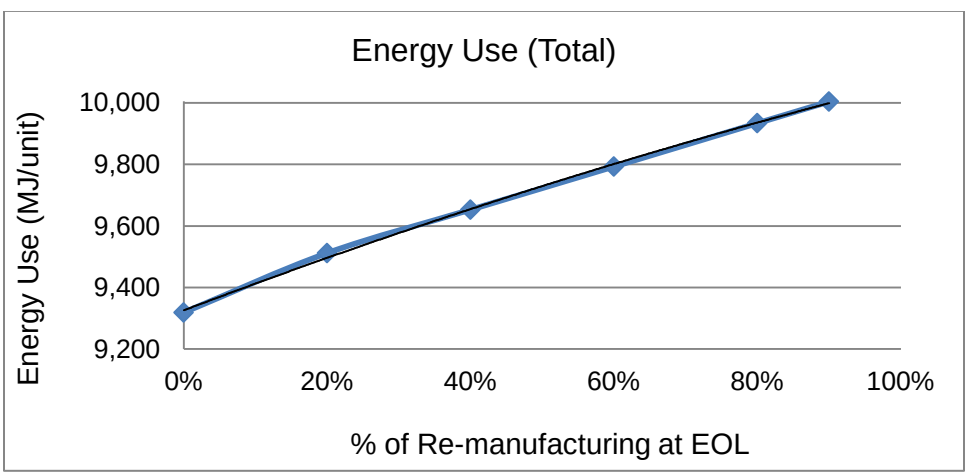

Figure 4-19 Variation curve for total energy use of remanufacturing EOL products

$$y_{eu_{total}} = -148.7\,x^2 - 880.85\,x + 9326.1 \tag{4-14}$$

Water Use

Table 4-14 shows how water use changes when the ratio of remanufactured EOL product varies from 0% to 90%. In the PM and the M stages, the water use decreases linearly as a result of remanufacturing old products.

Table 4-14 Water use for various ratio of remanufactured EOL product

% Re-manufacturing	Water (Kg/unit)				
	PM	M	U	PU	Total
0%	616.59	10.41	0.00	0.00	627.00
20%	493.67	8.33	0.00	942.00	1,444.00
40%	369.75	6.25	0.00	1490.00	1,866.00
60%	246.84	4.16	0.00	2040.00	2,291.00
80%	123.92	2.08	0.00	2580.00	2,706.00
90%	62.60	1.04	0.00	2860.00	2,923.64

In the PU stage, the water use shows a tremendous increase as the ratio of remanufactured EOL product increases, since large quantity of water is needed for the cleaning process. This trend can be represented by the curve shown in Figure 4-20, and it can be expressed by Eqn. (4-15).

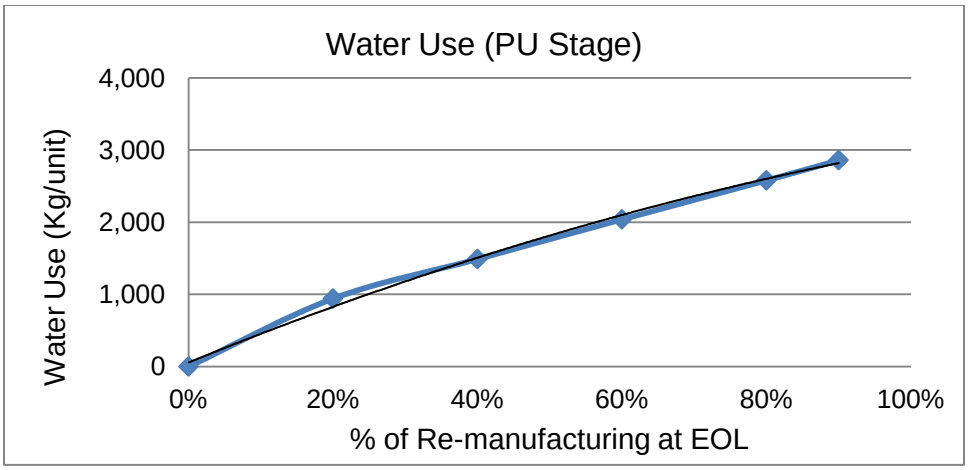

Figure 4-20 Variation curve for water use at the PU stage of remanufacturing EOL products

$$y_{wu_{pu}} = -1118.9\,x^2 + 4075.7\,x + 56.9 \quad (4\text{-}15)$$

Total water use for four life-cycle stages increases when the ratio of remanufactured EOL product varies from 0% to 90. This variation can be represented by the curve shown in Figure 4-21, and it can be expressed by Eqn. (4-16).

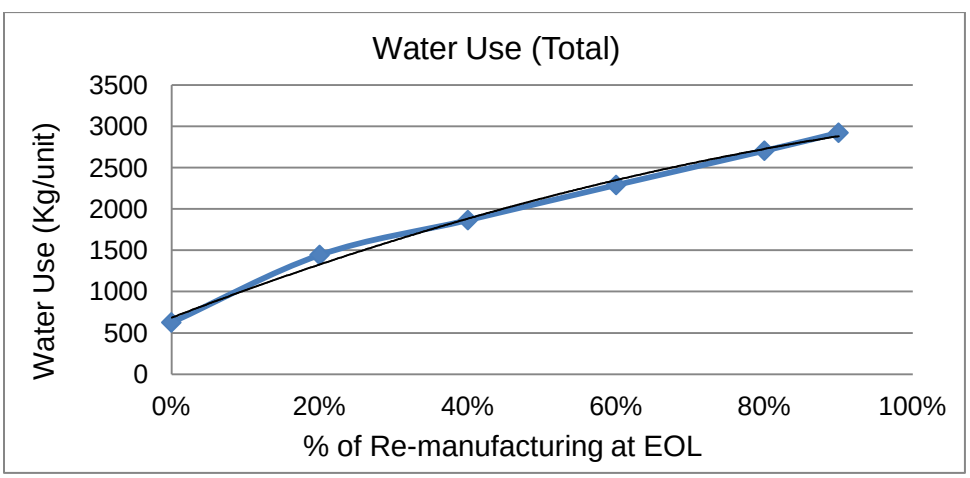

Figure 4-21 Variation curve for total water use of remanufacturing EOL products

$$y_{wu_{total}} = -1116.7\,x^2 + 3447.5\,x + 684.07 \quad (4\text{-}16)$$

Greenhouse Gas Emissions

Table 4-15 shows the changes of Greenhouse Gas emission when the ratio of remanufactured EOL product varies from 0% to 90%. In the PM and the M stages, the Greenhouse Gas emissions decrease linearly because of less involvement of the virgin materials.

Table 4-15 Greenhouse Gas emission for various ratio of remanufactured EOL product

% Re-manufacturing	Greenhouse Gas emission (Kg/unit)				
	PM	M	U	PU	Total
0%	55.52	52.35	278,370.71	0.00	278,478.58
20%	44.50	41.88	278,370.71	2.08	278,459.17
40%	33.25	31.41	278,370.71	3.59	278,438.96
60%	22.17	20.94	278,370.71	5.18	278,418.99
80%	11.09	10.47	278,370.71	6.77	278,399.03
90%	5.53	5.24	278,370.71	7.57	278,389.04

In the PU stage, the Greenhouse Gas emission shows a slight increase. This trend can be represented by the curve shown Figure 4-22, and it can be expressed by Eqn. (4-17).

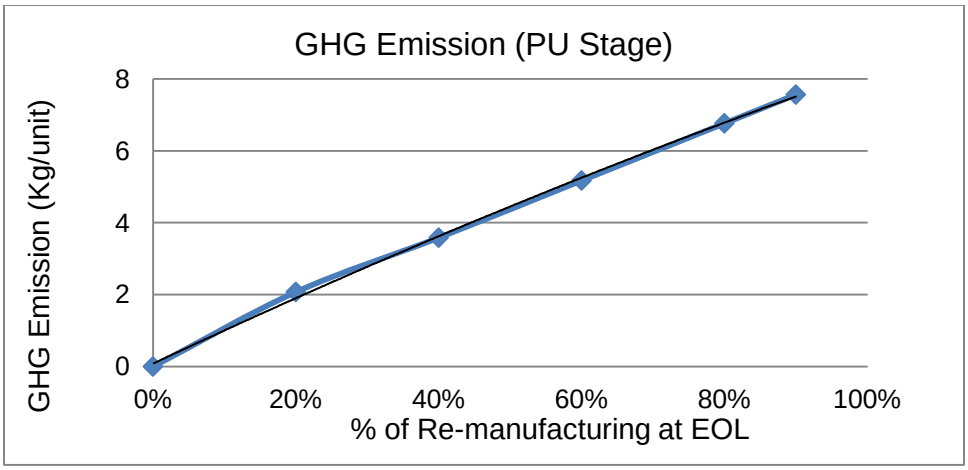

Figure 4-22 Variation curve for Greenhouse Gas emission at the PU stage of remanufacturing EOL products

$$y_{ge_{pu}} = -1.21\,x^2 + 9.34\,x + 0.082 \tag{4-17}$$

The total Greenhouse Gas emission for four life-cycle stages decreases when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be represented by the linear curve shown in Figure 4-23, and it can be expressed by Eqn. (4-18).

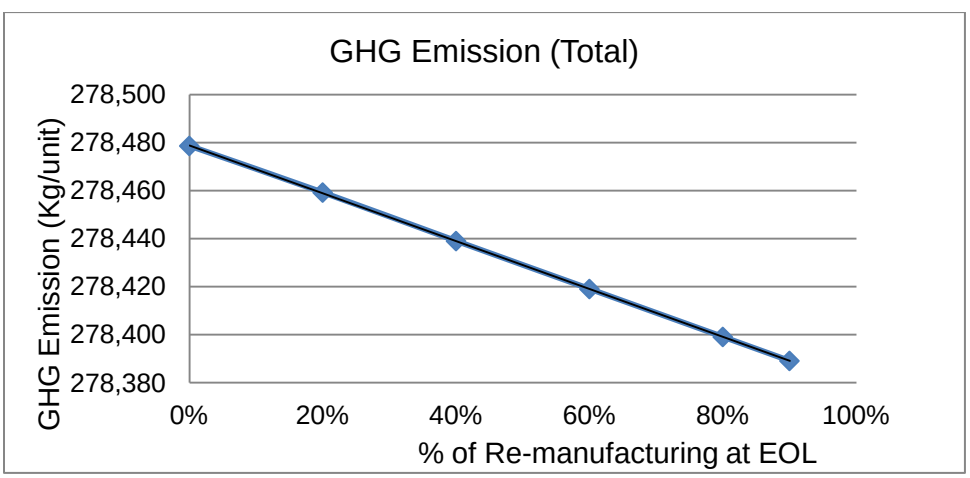

Figure 4-23 Variation curve for total Greenhouse Gas emission of remanufacturing EOL products

$$y_{ge_{total}} = -99.7\,x + 278479 \quad (4\text{-}18)$$

Direct Cost

The labor cost is directly related to the hours of labor involved at each product life-cycle stage. Its values of variation are shown in Table 4-16. Costs for other selective individual metrics are proportional to the usage. Tables 4-17, 4-18 and 4-19 show variations of material, energy, and water costs, respectively. Unlike the scenario of reusing EOL products, only material procurement price shows a linear decrease; all other costs – labor, energy, and water costs – show increasing trend. Reduced material cost is a result of remanufacturing the old components. Consequently, less virgin materials are needed to make new products. More labor is involved at the PU stage, and this leads to the increase in the labor cost. The increased cost of energy and water is the consequence of tremendous cleaning and the material deposition processes.

Table 4-16 Labor cost for various ratio of remanufactured EOL product

% Re-manufacturing	Labor cost ($/unit)				
	PM	M	U	PU	Total
0%	3.33	3.59	0.00	0.00	6.92
20%	2.67	2.87	0.00	6.38	11.92
40%	2.00	2.15	0.00	12.75	16.90
60%	1.33	1.43	0.00	19.13	21.89
80%	0.67	0.72	0.00	25.50	26.89
90%	0.33	0.36	0.00	28.69	29.38

Table 4-17 Material cost for various ratio of remanufactured EOL product

% Re-manufacturing	Material cost ($/unit)				
	PM	M	U	PU	Total
0%	45.00				45.00
20%	36.00				36.00
40%	27.00				27.00
60%	18.00				18.00
80%	9.00				9.00
90%	4.50				4.50

Table 4-18 Energy cost for various ratio of remanufactured EOL product

% Re-manufacturing	Energy cost ($/unit)				
	PM	M	U	PU	Total
0%	2.71	2.97	125.04	0.00	130.72
20%	2.17	2.38	125.04	3.84	133.43
40%	1.30	1.78	125.04	7.28	135.40
60%	0.52	1.19	125.04	10.62	137.37
80%	0.10	0.59	125.04	13.61	139.34
90%	0.01	0.30	125.04	14.98	140.33

Table 4-19 Water cost for various ratio of remanufactured EOL product

% Re-manufacturing	Water cost ($/unit)				
	PM	M	U	PU	Total
0%	0.94	0.02	0.00	0.00	0.96
20%	0.75	0.01	0.00	1.43	2.19
40%	0.56	0.01	0.00	2.26	2.83
60%	0.37	0.01	0.00	3.10	3.48
80%	0.19	0.00	0.00	3.92	4.11
90%	0.10	0.00	0.00	4.35	4.45

Even most cost related items show increases; when aggregating them to the total, the total value still shows a slight drop. The results are shown in Table 4-20. This decreasing trend can be represented by the curve shown in Figure 4-24, and it can be expressed by Eqn. (4-19).

Table 4-20 Total direct cost for various ratio of remanufactured EOL product

% Re-manufacturing	Total direct cost ($/unit)
0%	183.60
20%	183.54
40%	182.13
60%	180.74
80%	179.34
90%	178.66

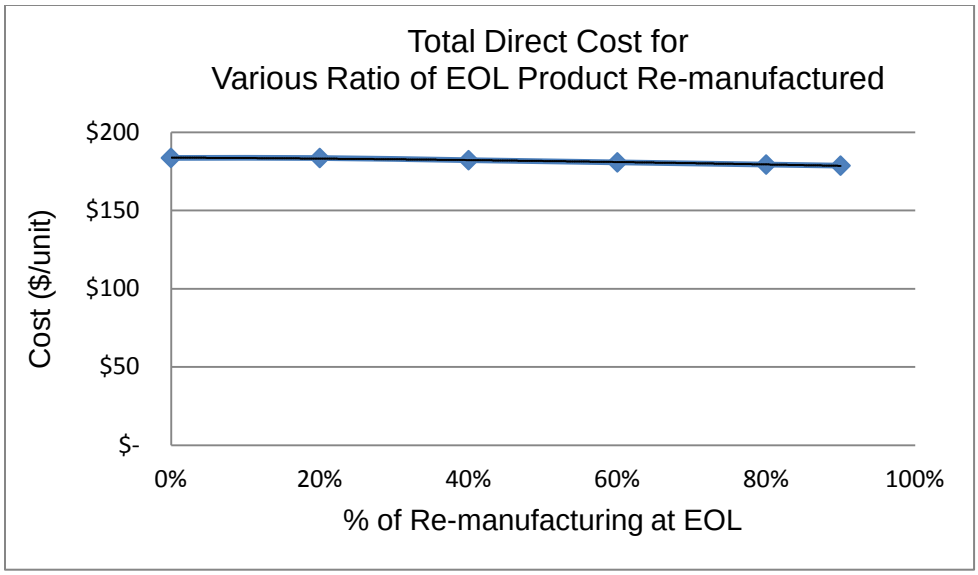

Figure 4-24 Variation curve for the total direct cost of remanufacturing EOL products

$$y_{cost_{total}} = -3.77x^2 - 2.46\,x + 183.94 \tag{4-19}$$

4.1.2.3 Comparison of Results and Summary

Even the energy use, water use, and their related costs increase when the percentage of EOL product remanufacturing gets larger, all other environmental impacts and the total direct cost show decreases. This is due to the outcome of applying the 6R activities.

From comparing the water use of remanufacturing 20% EOL products with 90%, it is obvious that the increase of water use is caused by the cleaning process at the PU stage, as shown in Figure 4-25. It shows that at the ratio of 20% of EOL product remanufactured at the PM stage contributes 34.8% of the total water use, while at the ratio of 90% of EOL product remanufactured 95.4% of the total water use is consumed by PU stage. Furthermore, measured water use in the PM stage contributes to get reduced from remanufacturing 90% of EOL products.

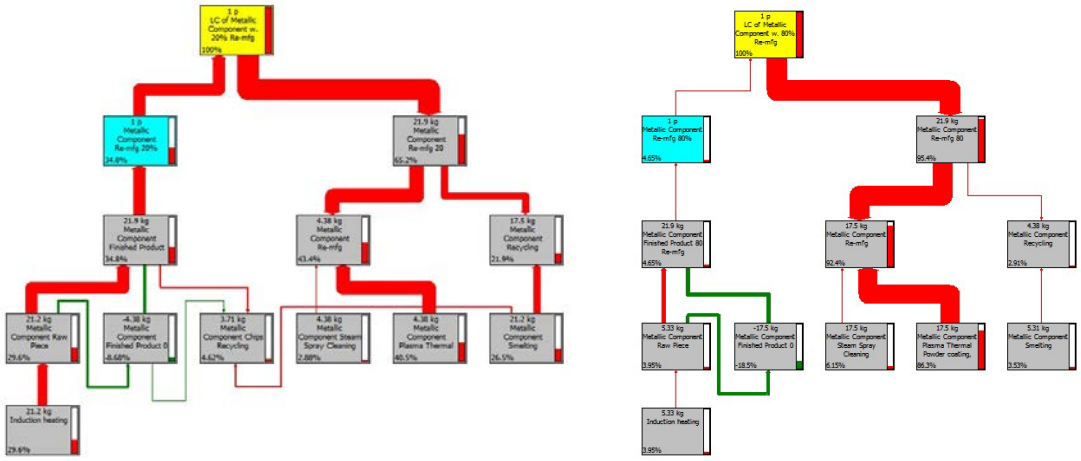

Figure 4-25 Comparison for water use at 20% vs. 90% ratio of remanufacturing EOL product

4.1.3 Modeling the Recycled EOL Product

4.1.3.1 Description

Figure 4-26 illustrates the decision flow for recycling the products at their EOL. Figure 4-27 shows all involved processes for recycling EOL products across four life-cycle stages.

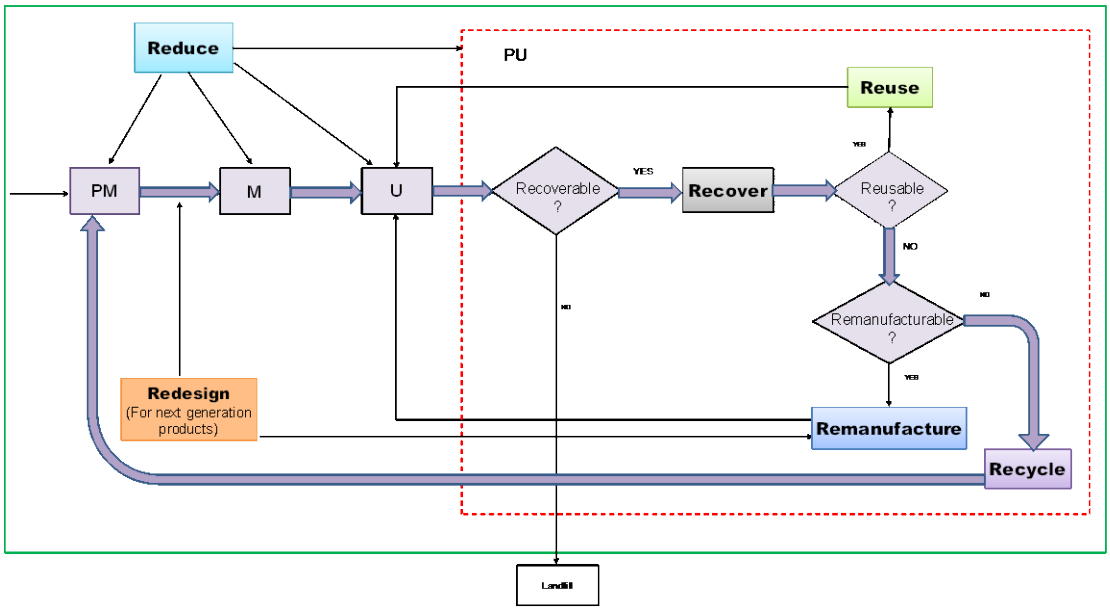

Figure 4-26 Decision flow diagram across four life-cycle stages for recycling EOL products

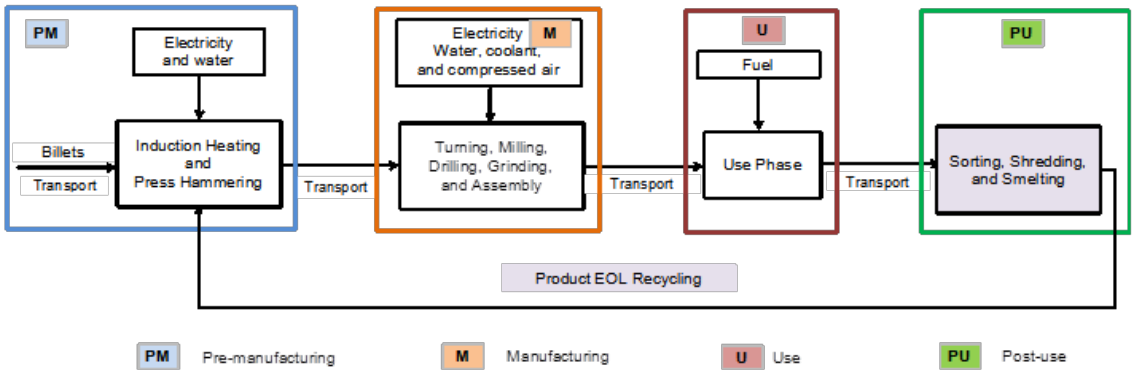

Figure 4-27 Process map across four life-cycle stages for recycling EOL products

In order to analyze the effects of recycling EOL products at the PU stage, it is assumed that all EOL products are qualified for neither reuse, nor remanufacturing. In this stage, EOL products can be recovered from material recovery eventually. It should be noted that most regulations related to end-of-life vehicles (ELV) require the OEMs to recycle more

than 95% of automobiles by weight at their EOL before year 2015. Thus, the varying ratio of this scenario is increased to 95% instead of 90% of previous two.

4.1.3.2 Results and analysis

Mass of Hazardous Material Use

Table 4-21 shows how the mass of hazardous material use changes when the ratio of recycled EOL product varies from 0% to 95%. In the PM stage, a decrease in the usage of hazardous material can be observed as less virgin material is used with increased material recycling. This trend can be represented by the curve shown in Figure 4-28, and it can be expressed by Eqn. (4-20).

Table 4-21 Mass of hazardous material use for various ratio of recycled EOL product

% Recycling	Mass of hazardous material use (mg/unit)				
	PM	M	U	PU	Total
0%	119.50	40,000	0.00	0.00	40,119.50
20%	110.50	40,000	0.00	16.15	40,126.65
40%	100.90	40,000	0.00	16.85	40,117.75
60%	91.20	40,000	0.00	17.55	40,108.75
80%	81.40	40,000	0.00	18.75	40,100.15
90%	76.60	40,000	0.00	18.50	40,095.10
95%	74.20	40,000	0.00	18.77	40,092.97

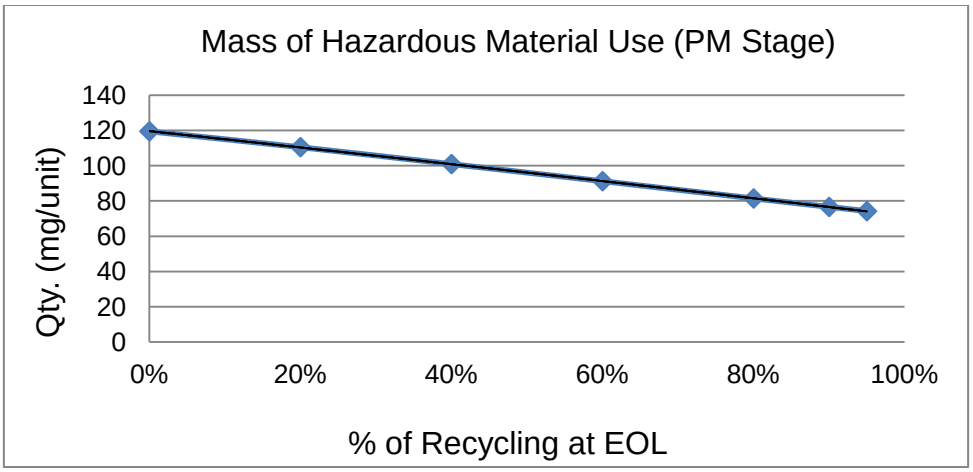

Figure 4-28 Variation curve for mass of hazardous material use at the PM stage of recycling EOL products

$$y_{mh_{pm}} = -1.97\,x^2 - 46.02\,x + 119.6 \tag{4-20}$$

In the M stage, the mass of hazardous material use stays constant as the manufacturing processes stay unchanged regardless the percentage of recycled materials involved. In the PU stage, it shows a rapid increase when the ratio of recycled EOL product decreases to 20%; then it decreases slowly. This trend can be represented by the curve shown in Figure 4-29, and it can be expressed by Eqn. (4-21).

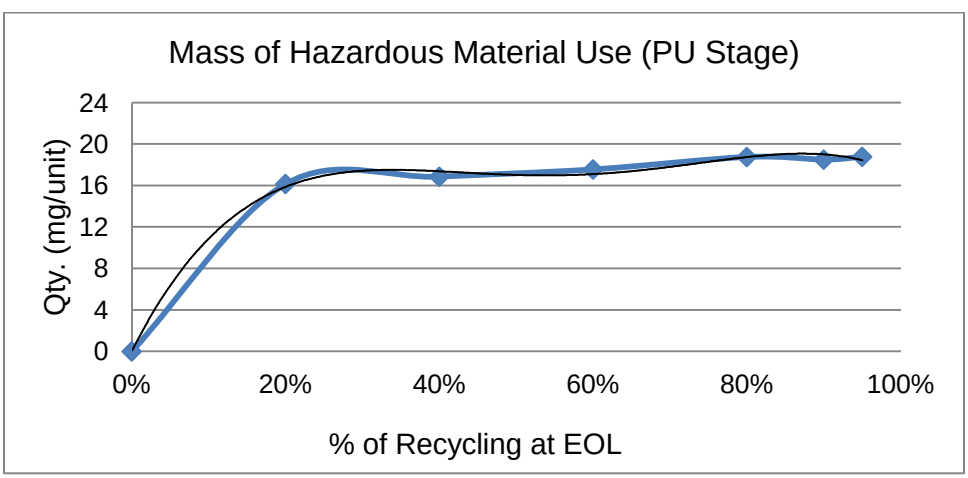

Figure 4-29 Variation curve for mass of hazardous material use at the PU stage of recycling EOL products

$$y_{mh_{pu}} = -231.39x^4 + 539.41x^3 - 437.96\,x^2 + 146.97\,x + 0.056 \quad (4\text{-}21)$$

The total hazardous material used for four life-cycle stages increases slightly at 20% recycling ratio, then it decreases tremendously along with the percentage of recycling EOL product goes to 95%. This is because of the rapid rate of decrease in the PM stage when compared with the rate of increase in PU stage. This trend can be represented by the curve shown in Figure 4-30, and it can be expressed by Eqn. (4-22).

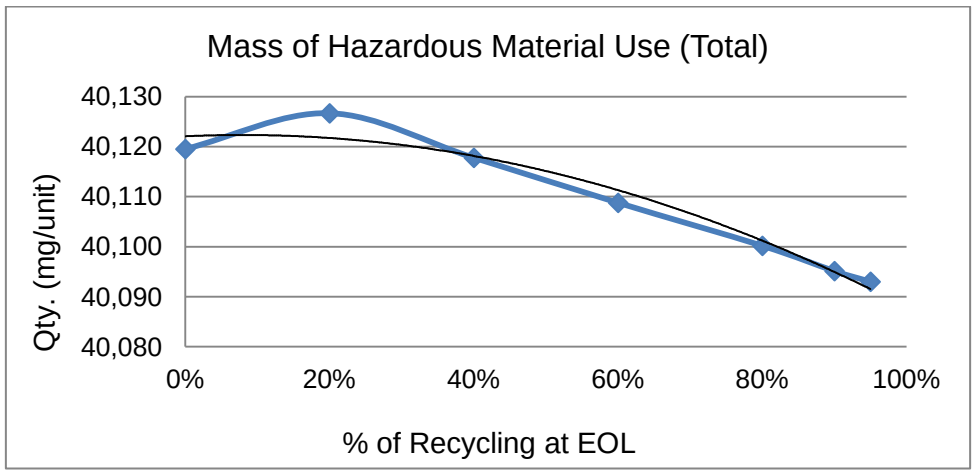

Figure 4-30 Variation curve for total mass of hazardous material use of recycling EOL products

$$y_{mh_{total}} = -\ 40.63\,x^2 + 6.42\,x + 40122 \quad (4\text{-}22)$$

Energy Use

Table 4-22 shows how the energy use changes when the ratio of recycled EOL product varies from 0% to 95%. In the PM stage, energy use decreases when the amount of virgin material used decreases. This trend can be represented by the curve shown in Figure 4-31, and it can be expressed by Eqn. (4-23).

Table 4-22 Energy use for various ratio of recycled EOL product

% Recycling	Energy (MJ/unit)				
	PM	M	U	PU	Total
0%	183.25	211.75	8,913.56	0.00	9,308.56
20%	163.12	211.75	8,913.56	10.12	9,298.56
40%	134.00	211.75	8,913.56	20.25	9,279.56
60%	103.88	211.75	8,913.56	30.37	9,259.56
80%	74.76	211.75	8,913.56	40.49	9,240.56
90%	59.69	211.75	8,913.56	45.55	9,230.56
95%	49.63	211.75	8,913.56	50.62	9,225.56

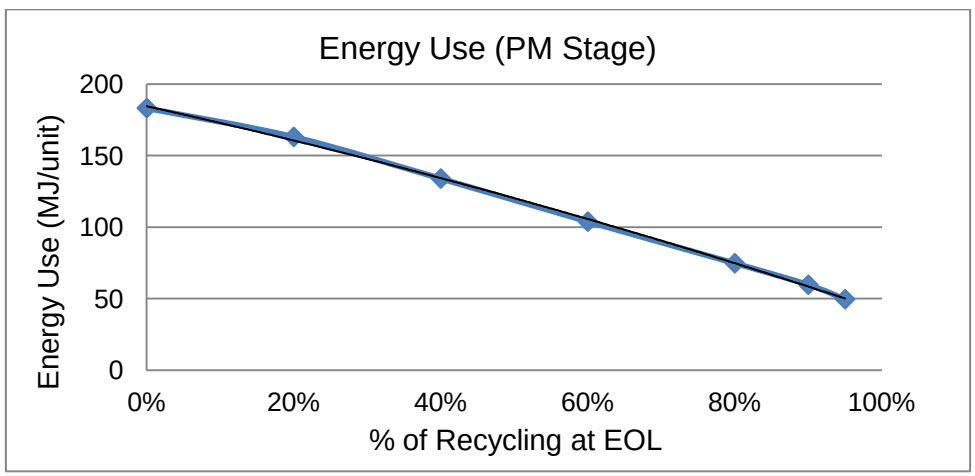

Figure 4-31 Variation curve for energy use at the PM stage of recycling EOL products

$$y_{eu_{pm}} = -28.93\,x^2 - 114.03\,x + 184.52 \tag{4-23}$$

In the PU stage, energy use increases linearly as the ratio of recycled EOL product increases, because more EOL product recycling activities are involved.

The total energy use for four life-cycle stages shows a dramatic decrease when the ratio of recycled EOL product varies from 0% to 95% because of the rapid decrease in the PM stage. This trend can be represented by the curve shown in Figure 4-32, and it can be expressed by Eqn. (4-24).

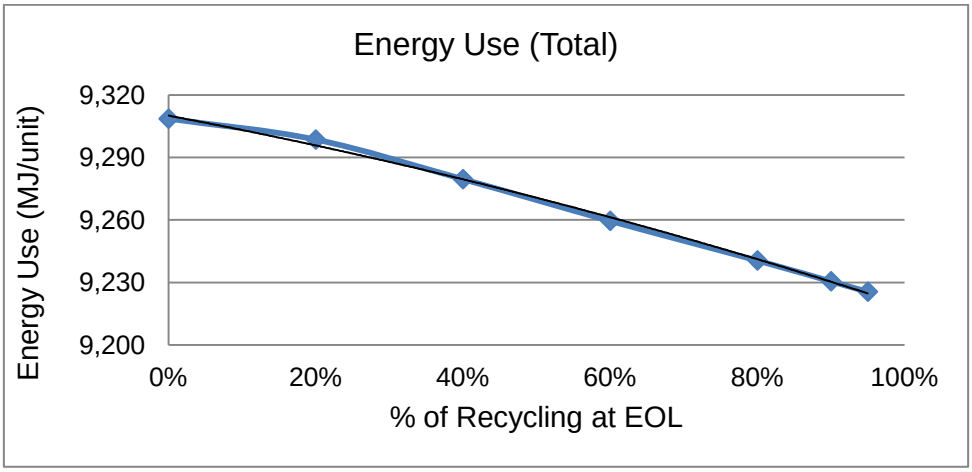

Figure 4-32 Variation curve for total energy use of recycling EOL products

$$y_{eu_{total}} = -24.39\,x^2 - 66.63\,x + 9310.1 \tag{4-24}$$

Water Use

Table 4-23 shows how water use changes when the ratio of recycled EOL product varies from 0% to 95%. In the PM stage, the water use decreases is a result of using more recycled materials to make new products. This trend can be represented by the curve shown in Figure 4-33, and it can be expressed by Eqn. (4-25).

Table 4-23 Water use for various ratio of recycled EOL product

% Recycling	Water (Kg/unit)				
	PM	M	U	PU	Total
0%	533.59	10.41	0.00	0.00	544.00
20%	528.59	10.41	0.00	78.90	617.90
40%	440.59	10.41	0.00	158.00	609.00
60%	352.59	10.41	0.00	237.00	600.00
80%	264.59	10.41	0.00	316.00	591.00
90%	220.59	10.41	0.00	355.00	586.00
95%	196.59	10.41	0.00	375.00	582.00

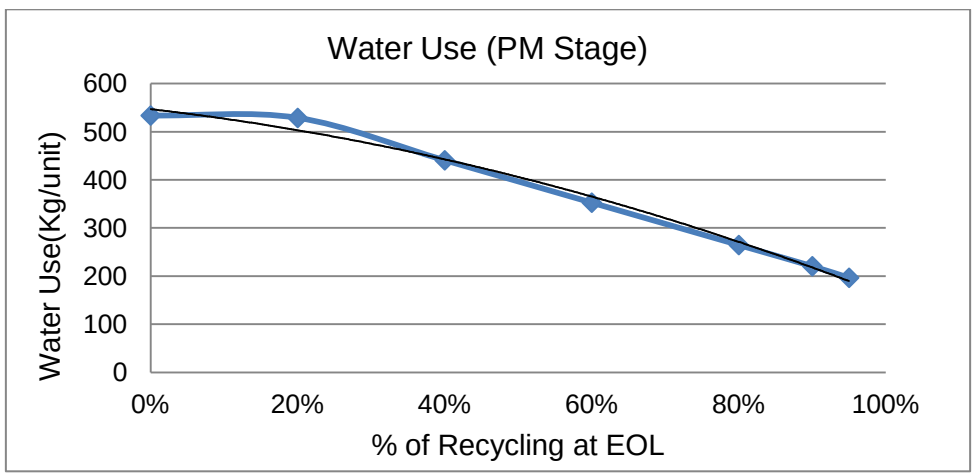

Figure 4-33 Variation curve for water use at the PM stage of recycling EOL products

$$y_{wu_{pm}} = -209.49\,x^2 - 176.86\,x + 546.88 \quad (4\text{-}25)$$

In the PU stage, more recycling activities involved results in a linear increase in the use of water.

Total water use for four life-cycle stages increases when the ratio of recycled EOL product increases to 20%, then it drops as the percentage of recycling EOL products increases to 95% as shown in Figure 4-34. This trend can be expressed by Eqn. (4-26).

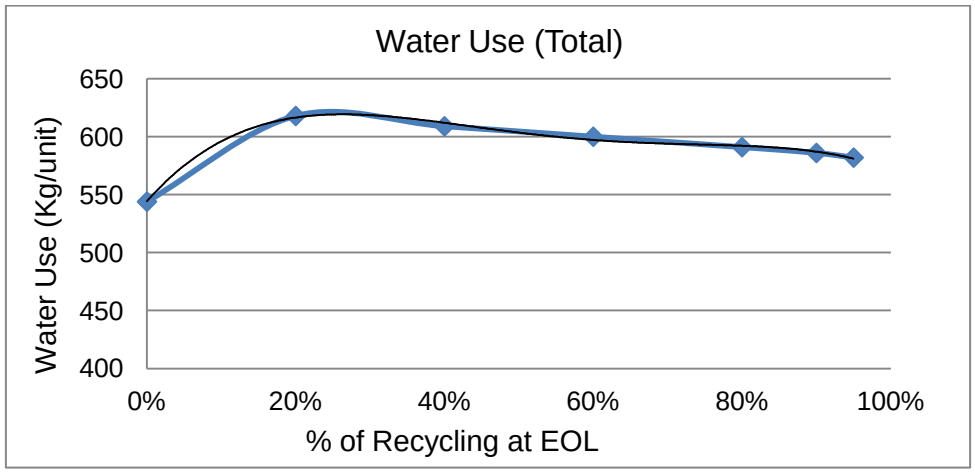

Figure 4-34 Variation curve for total water use of recycling EOL products

$$y_{wu_{total}} = -1200.5\,\mathrm{x}^4 + 2821.4\,\mathrm{x}^3 - 2314.4\,x^2 + 720.27\,x + 544.3 \qquad (4\text{-}26)$$

Greenhouse Gas Emissions

Table 4-24 shows how Greenhouse Gas emission changes when the ratio of recycled EOL product varies from 0% to 95%. In the PM stage, the Greenhouse Gas emission shows a slight decrease. This trend can be represented by the curve shown in Figure 4-35, and it can be expressed by Eqn. (4-27).

Table 4-24 Greenhouse Gas emission for various ratio of recycled EOL product

% Recycling	Greenhouse Gas emission (Kg/unit)				
	PM	M	U	PU	Total
0%	55.46	52.35	278,370.71	0.00	278,478.52
20%	55.28	52.35	278,370.71	0.09	278,478.43
40%	54.88	52.35	278,370.71	0.17	278,478.11
60%	54.67	52.35	278,370.71	0.24	278,477.98
80%	54.44	52.35	278,370.71	0.32	278,477.82
90%	54.33	52.35	278,370.71	0.36	278,477.75
95%	54.28	52.35	278,370.71	0.38	278,477.72

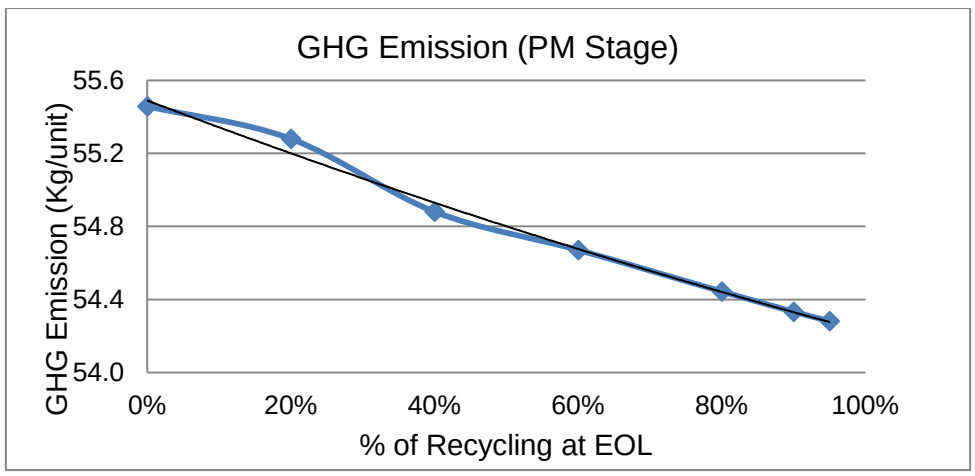

Figure 4-35 Variation curve for Greenhouse Gas emission at the PM stage of recycling EOL products

$$y_{ge_{pm}} = 0.223\,x^2 + 1.49\,x + 55.49 \tag{4-27}$$

More recycling activities lead to a slight increase in the amount of emissions in the PU stage.

The total Greenhouse Gas emission for four life-cycle stages decreases slightly as the percentage of recycling EOL products increases from 0% to 95%. This trend can be represented by the curve shown in Figure 4-36, and it can be expressed by Eqn. (4-28).

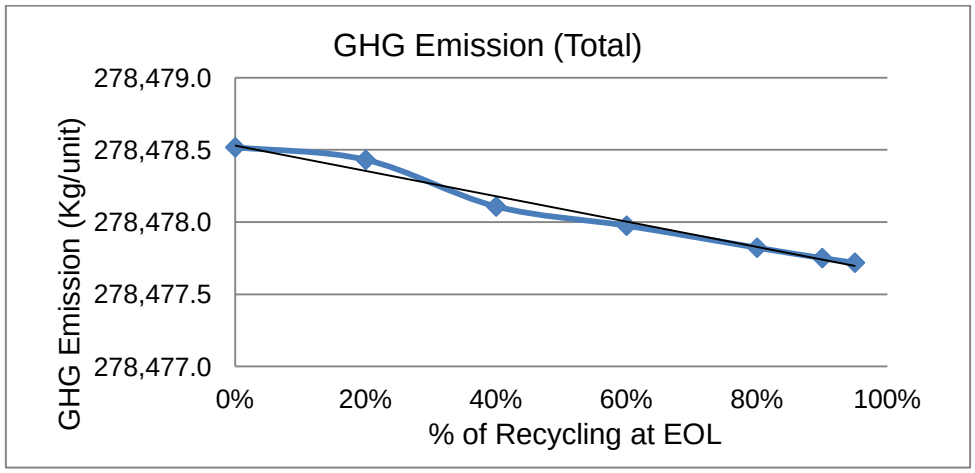

Figure 4-36 Variation curve for total Greenhouse Gas emission of recycling EOL products

$$y_{ge_{total}} = -0.877\,x + 278479 \tag{4-28}$$

Mass of Waste Disposed

Table 4-25 shows how mass of waste disposed changes when the ratio of recycled EOL product varies from 0% to 95%. In the PM, M, and the U stages, all values remain zero. It is assumed that steel scraps generated from manufacturing processes are 100% recycled; thus there is no waste disposed to landfill. In the PU stage, 20% of total mass of the product is assumed to be disposed each time to landfill or another storage place other than getting recovered.

Table 4-25 Mass of waste disposed for various ratio of recycled EOL product

% Recycling	Mass of waste disposed (Kg/unit)				
	PM	M	U	PU	Total
0%	0.00	0.00	0.00	21.92	21.92
20%	0.00	0.00	0.00	17.54	17.54
40%	0.00	0.00	0.00	13.15	13.15
60%	0.00	0.00	0.00	8.77	8.77
80%	0.00	0.00	0.00	4.38	4.38
90%	0.00	0.00	0.00	2.19	2.19
95%	0.00	0.00	0.00	1.10	1.10

Direct Cost

Variations of the labor cost are shown in Table 4-26. It is directly proportional to the labor hours spent at each product life-cycle stage to make the products. Costs for other selected metrics are directly proportional to the amount of usage. Tables 4-27, 4-28, and 4-29 show variations of material, energy, and water costs, respectively. Both energy cost and water cost show decreases. The material purchasing price keeps constant as the market price is not affected by the amount of recycled material used. There is an increase in the labor cost, which is caused from more labor hours spent on the EOL product recycling activity.

Table 4-26 Labor cost for various ratio of recycled EOL product

% Recycling	Labor cost ($/unit)				
	PM	M	U	PU	Total
0%	3.33	3.59	0.00	0.00	6.92
20%	2.67	3.59	0.00	4.50	10.76
40%	2.00	3.59	0.00	9.00	14.59
60%	1.33	3.59	0.00	13.50	18.42
80%	0.67	3.59	0.00	18.00	22.26
90%	0.33	3.59	0.00	20.25	24.17

Table 4-27 Material cost for various ratio of recycled EOL product

% Recycling	Material cost ($/unit)				
	PM	M	U	PU	Total
0%	45.00				45.00
20%	45.00				45.00
40%	45.00				45.00
60%	45.00				45.00
80%	45.00				45.00
90%	45.00				45.00

Table 4-28 Energy cost for various ratio of recycled EOL product

% Recycling	Energy cost ($/unit)				
	PM	M	U	PU	Total
0%	2.57	2.97	125.04	0.00	130.58
20%	2.28	2.97	125.04	0.15	130.44
40%	1.86	2.97	125.04	0.30	130.17
60%	1.43	2.97	125.04	0.45	129.89
80%	0.57	2.97	125.04	0.60	129.18
90%	0.80	2.97	125.04	0.67	129.48

Table 4-29 Water cost for various ratio of recycled EOL product

% Recycling	Water cost ($/unit)				
	PM	M	U	PU	Total
0%	0.81	0.02	0.00	0.00	0.83
20%	0.80	0.02	0.00	0.12	0.94
40%	0.67	0.02	0.00	0.24	0.93
60%	0.54	0.02	0.00	0.36	0.92
80%	0.26	0.02	0.00	0.48	0.76
90%	0.34	0.02	0.00	0.54	0.90

Values of the total direct cost can be calculated from combining all the direct costs together for each varying ratio of recycled EOL product. From the results shown in Table 4-30, a very slight increase can be observed. This trend can be represented by curve shown in Figure 4-37, and it can be expressed by Eqn. (4-29).

Table 4-30 Total direct cost for various ratio of recycled EOL product

% Recycling	Total direct cost ($/unit)
0%	183.33
20%	187.14
40%	190.69
60%	194.23
80%	197.20
90%	199.55

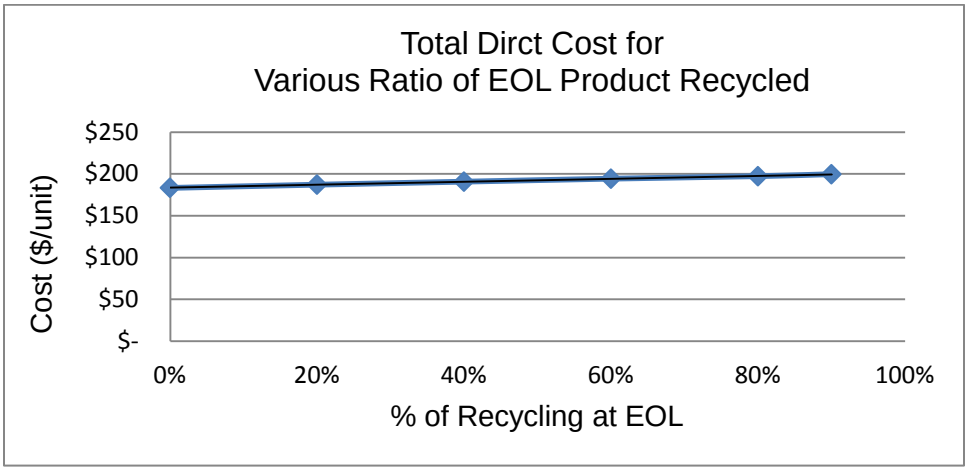

Figure 4-37 Variation curve for the total direct cost of recycling EOL products

$$y_{cost_{total}} = 17.634\,x + 183.49 \tag{4-29}$$

4.1.3.3 Comparison of Results and Summary

All results related to the footprints and environmental impacts show decreasing trend. This is an outcome of using recycled materials to replace virgin materials. Only the total direct cost shows a slight increase because of a labor cost increase.

Despite the minor increase in the total direct cost, using recycled material to make new products – compared with not conducting any product EOL activities - is a much more sustainable practice. For example, the difference in carbon dioxide emission can be observed from Figure 4-38, when the product made with 20% of recycled material is compared with the one made with 90% of recycled material. The major contributor of carbon dioxide is shifted from the PM stage to the energy generation. Furthermore, more carbon dioxide is avoided for the model with 90% recycled materials used. It is visually represented by the green line.

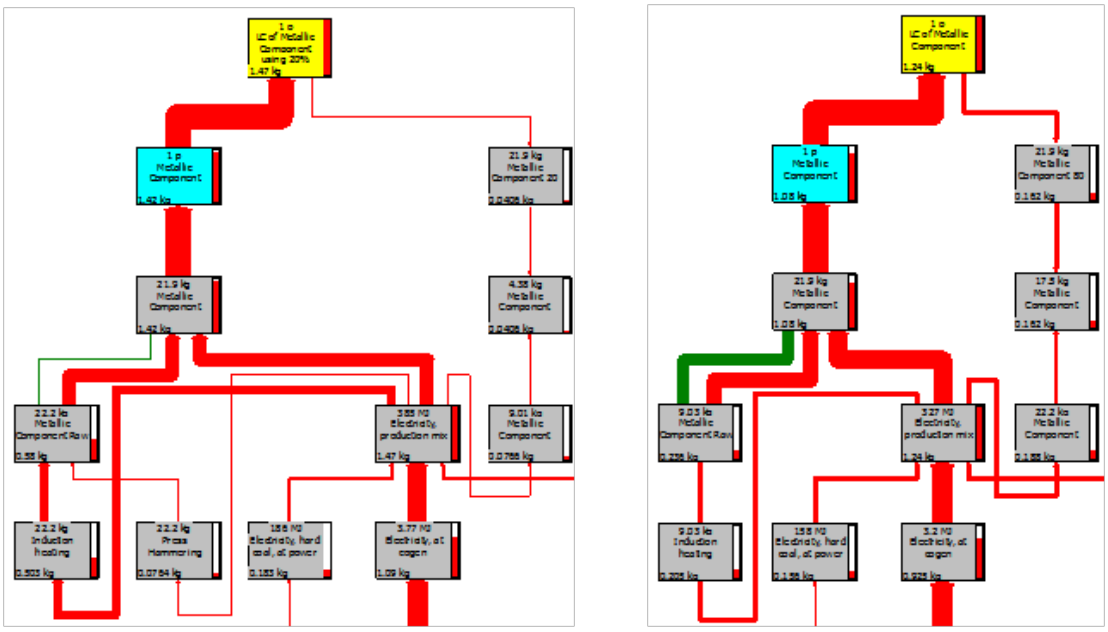

Figure 4-38 Comparison for carbon dioxide at 20% vs. 90% ratio of recycling EOL product

4.1.4 Summary

The connections among the 6R activities are systematically presented in this chapter. The improvements of overall product sustainability by applying the 6R methodology are validated via modeling the total life-cycle stages of metallic automotive components.

Comparing the results of modeling the products with three different EOL scenarios, from the perspective of environmental impacts, all footprints and environmental related issues show various degrees of decreases with the application of EOL product reuse, remanufacturing, and recycling; except for the energy use and the water use for the remanufacturing scenario. For the direct economic effects, the total direct cost for both EOL product reuse and remanufacturing decreases when more EOL activities are involved; while a slight cost increase is observed for the EOL recycling scenario.

There is a trade-off between energy and water use and the costs spent. It is intuitive that there should be an optimal mix of EOL practice to obtain the most sustainable product prototype. Therefore, a mathematical model, minimizing costs, energy use and water use at the same time, will be presented in the next section of this chapter.

4.2 Mathematical Model for Product Sustainability Metrics

4.2.1 Assumptions and Descriptions of the Model Formulation

The mathematical model formulated in this study is a non-linear program with multiple objectives to minimize the total direct cost, total energy use, and total water use simultaneously. The model was set up and solved in Excel Solver. Figure 4-39 illustrates a possible decision mix for various EOL product strategic options. The assumptions of the model are listed below.

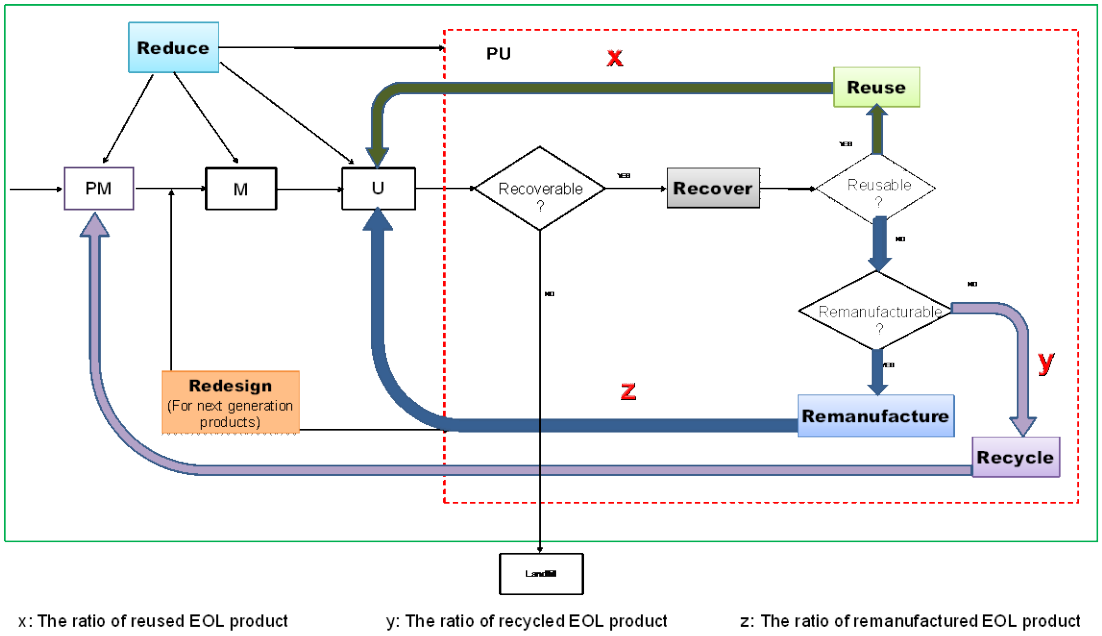

Figure 4-39 Combined loop for various EOL product strategic options

- The metallic automotive component is a stand-alone manufactured component from a single material.

- The mathematical model is generic.

- Reused products, remanufactured products, as well as the new products made with recycled material, will acquire the same or superior performance than the ones manufactured with virgin material.

- The distance between the EOL product supplier and the component rebuilder (or the OEM), and the material recycler is approximately the same.

4.2.2 Mathematical Model

The notations used in the formulation of the mathematical model are listed in Table 4-31.

Table 4-31 Notations used in the formulation of the mathematical model

Notations	Descriptions
x	The ratio of reused EOL product
y	The ratio of recycled EOL product
z	The ratio of remanufactured EOL product
$z_{cost_{total}}$	Total direct cost
$z_{eu_{total}}$	Total energy use
$z_{wu_{total}}$	Total water use
α	Weight assigned to the function of total direct cost
β	Weight assigned to the function of total energy use
g	Weight assigned to the function of total water use

Decision variables are defined as follows,

Let x to be the ratio of reused EOL product;

Let y to be the ratio of recycled EOL product; and

Let z to be the ratio of remanufactured EOL product

The mathematical correlations of the total direct cost, total energy use, and total water use were developed in the previous section. These relations are expressed with respect to the varying ratio of the EOL product activities. The total direct cost in this study involves labor cost, material cost, energy cost, and water cost. Electricity is the main energy support throughout the entire life-cycle; thus, electricity consumption is considered for energy use. Water use includes all forms of water, including heat and vapor. Based on the expressions obtained in Section 4.1 for the scenarios of EOL product reuse, recycling, and remanufacturing, the total direct cost for the mixed product EOL activities, with respect to the decision variables defined, can be expressed Eqn. (4-30).

$$z_{cost_{total}} = (-41.51x + 184.19) + (17.63y + 183.49) + (-3.77z^2 - 2.46z + 183.9) \tag{4-30}$$

Based on the expressions obtained for the total energy use for three different EOL scenarios, the total energy use for the mixed product EOL activities, with respect to the decision variables defined, can be expressed by Eqn. (4-31).

$$z_{eu_{total}} = (-149.4x^2 - 269.67x + 9326.1) + (-24.39y^2 - 66.63y + 9310.1) + (-148.7z^2 + 880.85z + 9326.1) \tag{4-31}$$

Similarly, the total water use for the mixed product EOL activities, with respect to the decision variables defined, can be expressed by Eqn. (4-32).

$$z_{wu_{total}} = (3061.7x^3 - 5210.9x^2 + 1843.1x + 673.52) + (-1200.5x^4 + 2821.4x^3 - 2314.4y^2 + 720.27y + 544.3) + (-1116.7z^2 + 3447.5z + 684.07) \quad (4\text{-}32)$$

The objective of the mathematical model is to minimize the total direct cost, energy use, and water use simultaneously. However, the units carried by three objectives are different ($/unit is for the total direct cost, MJ/unit is for the total energy use, and Kg/unit is for the total water use). It is necessary to normalize them in order to combine them together. This can be achieved by dividing its benchmark numbers. Set c_1 = $ 500, c_2 = 28,004.12 MJ, and c_3 =2,933 Kg as benchmarks for$z_{cost_{total}}$, $z_{eu_{total}}$, and $z_{wu_{total}}$ respectively. In order to analyze the effects of changing the importance of each objective, arbitrarily weights - denoted by *a, b, and g* – are assigned to each of the objectives. Combining three mathematical functions into one, the objective function can be expressed by Eqn. (4-33).

$$Minimize: Z = \frac{\alpha \times z_{cost_{total}}}{c_1} + \frac{\beta \times z_{eu_{total}}}{c_2} + \frac{\gamma \times z_{wu_{total}}}{c_3} \quad (4\text{-}33)$$

Constrains of the mathematical model are described as follows.

To meet the directives initiated by both UN and EPA, ratio of reuse and recovery shall be at least 75% by average weight per vehicle by the year 2015 (EPA 2008), (EU 2000), 75% of EOL product reused is set as the upper bound of this particular constrain. Similarly, because the minimum of 95% by weight per car is required for recycling, the upper bound of the constrain for the percentage of recycling is set as 95%. Since there are no specific statements in the ELV regulations regarding the rate of remanufacturing, it is assumed that it could reach up to 100% as an ideal case. Since this is a percentage mix problem, total of the percentage mix has to sum up to one. The same is true to the sum of the random weights assigned, which must equal to one as well. It is impossible for any mix of this blending problem to be a negative value; therefore, all decision variables and arbitrary weights are constrained to be equal to or larger than zero.

Based on the above descriptions, the formulation of the mathematical model can be summarized as follows,

- Objective function:

$$Minimize\ Z = \frac{\alpha \times z_{cost_{total}}}{c_1} + \frac{\beta \times z_{eu_{total}}}{c_2} + \frac{\gamma \times z_{wu_{total}}}{c_3}$$

where,

$z_{cost_{total}} = (-41.51x + 184.19) + (17.63y + 183.49) + (-3.77z^2 - 2.46z + 183.9)$,

$z_{eu_{total}} = (-149.4x^2 - 269.67x + 9326.1) + (-24.39y^2 - 66.63y + 9310.1) + (-148.7z^2 + 880.85z + 9326.1)$,

$z_{wu_{total}} = (-1111.7x^2 + 519.81x + 684.12) + (-210.36y^2 + 218.69y + 557.23) + (-1116.7z^2 + 3447.5z + 684.07)$,

- Subject to:

$x \leq 75\%$

$y \leq 95\%$

$z \leq 100\%$

$x + y + z = 1$

$\alpha + \beta + \gamma = 1$

$x \geq 0, y \geq 0, z \geq 0, \alpha \geq 0, \beta \geq 0, \gamma \geq 0$

4.2.3 Results and Discussion

Table 4-32 shows the calculated values in the Excel sheet for the mathematical model set up. It shows decision variables, constraints, weights, benchmark values, and the output results for the total direct cost, energy use, and water use when weight 0.9 is assigned to the objective of the total direct cost, while the other two objectives share the equal weight of 0.05.

Table 4-32 Mathematical model set-up in Excel sheet

		Decision Variables				**Constrains**			
		Reused	Recycled	Re-mfred	Actual %		Requirement		
Decision Variables	Reused	**75.00%**	**0.00%**	**0.00%**	75.00%	≥	0%	≤	75%
	Recycled	**0.00%**	**2.80%**	**0.00%**	2.50%	≥	0%	≤	95%
	Re-mfred	**0.00%**	**0.00%**	**22.30%**	22.50%	≥	0%	≤	100%
	Total	75.00%	2.80%	22.30%	100%	=	100%		
Costs	Reused	153.06	0	0	$ 153.06		0.90		
	Recycled	0	183.98	0	$ 183.98		$ 500.00		
	Re-mfred	0	0	182.96	$ 182.96		$ 520.00		
Energy Use	Reused	9,039.81	0	0	9,039.81		0.05		
	Recycled	0	9,308.22	0	9,308.22		28,004.12		
	Re-mfred	0	0	9,515.13	9,515.13		27,863.16		
Water Use	Reused	380.37	0	0	380.37		0.05		
	Recycled	0	562.71	0	562.71		2,933.00		
	Re-mfred	0	0	1,397.33	1,397.33		2,340.41		1.03

By assigning different weights to the objectives and solving the model, results are obtained by using the Solver, and these results are presented in Table 4-33. Solutions obtained for the problem indicate that the importance of the objective is an influencing factor to the decisions to be made. When α (the importance of the direct cost objective function) is assigned as 0.1 and β and g (the importance of the energy use and the water use objective functions) share equal weight 0.45, it suggests that a mix of 75% reusing EOL products and 25% material recycling is an optimum solution to treatment the EOL products. When three objectives share equal importance, the solution suggests 75% of reusing, 23.78% of recycling, and 1.32% of remanufacturing of the EOL products. When α is assigned as 0.6, and β and g for the other two footprints are assigned as 0.2, the result shows a mix of 75% of reusing, 16.35% of recycling, and 8.65% of remanufacturing the EOL products. And, when the economic objective function carries the highest weight 0.9 and the other two carry 0.05, the solution indicates 75% of reusing, 2.8% or recycling, and 22.3% of remanufacturing EOL products.

From the results shown in the table, a pattern can be observed: when the economic objective carries the highest importance, the associated cost value is relatively the lowest; when the environmental objectives carry the highest importance, their values are the lowest. Moreover, along with the increasing weight for the economic objective, the objective value gets larger.

Table 4-33 Results for different weights assigned

				Reused	**Recycled**	**Re-mfred**	**Costs**	**Energy**	**Water**
a	***b***	***g***	Obj V.	***x***	***y***	***z***	($/unit)	(MJ/unit)	(Kg/unit)
0.1	0.45	0.45	0.81	75.00%	25.00%	0.00%	$ 524.66	27,657.83	1,683.55
0.34	0.33	0.33	0.88	75.00%	23.78%	1.32%	$ 524.41	27,670.44	1,728.56
0.6	0.2	0.2	0.96	75.00%	16.35%	8.65%	$ 522.90	27,739.54	1,965.95
0.9	0.05	0.05	1.03	75.00%	2.80%	22.30%	$ 520.00	27,863.16	2,340.41

4.2.4 Summary

To achieve the goal of finding the optimum EOL decision, a mathematical model was developed and programmed to minimize the total direct cost, energy use, and water use at the same time. The model is a multi-objective non-linear program. It is subject to non-negative constraints, as well as some associated target numbers required by available initiatives.

Multiple sets of results were obtained for various weights assigned to three different objectives. The solutions indicate the reuse of products at the EOL as much as possible, while recycling and remanufacturing activities can vary depending on the importance of footprints and the total direct cost. If the footprints play a more important role than the economic term, material recycling is recommended; and vice versa.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In this thesis, an introduction to the areas related to the study of research was presented in Chapter 1. Numerous relevant previous publications were studied and reviewed in Chapter 2. A new metric-based LCA method for assessing the sustainability performance of metallic automotive components was presented in Chapter 3. The methodology was demonstrated through modeling the four life-cycle stages of metallic automotive components; and a mathematical model to find an optimum mix of EOL activities (reuse, remanufacturing, and recycling EOL products) were presented in Chapter 4. Finally, conclusions to this study are drawn in this chapter with some remarks on the future work needed.

5.1 Conclusions

In this research, a new metric-based LCA methodology was presented and demonstrated. Main emphasis of this research study is to integrate the 6R activities by modeling four life-cycle stages of metallic automotive components for improved product sustainability. Results have shown improved overall product sustainability. The improvements can be made quantitatively and comprehensively by using the *ProdSI* methodology, incorporated with 6R activities.

The mathematical model presented is a non-linear program with multiple objectives. It was aimed at minimizing the total direct cost, energy us, and water use concurrently. Various sets of solutions were obtained for different importance assigned to three objectives.

In brief, the outcome of this research shows that by applying the 6R methodology the overall product sustainability can be improved. Further, it demonstrates that involving the total life-cycle approach, TBL, elements and sub-elements of Design for Sustainability,

and the 6R activities lays a strong foundation for a comprehensive evaluation of product sustainability.

5.2 Future Work

Four life-cycle stages of metallic automotive components are modeled using publicly available data and information, and only with the data for the M stage from a local auto manufacturer and with minor adjustments. The research results leads to usable methods, but should be further investigated in the real world practices with more data from industries. However, it is recognized that collecting such data from industries could be a challenge.

The chosen product for this study is a stand-alone manufactured automotive component. Eventually, this methodology can be extended to analyze assembled products involving multiple components, and products made with composite materials are expected.

Per the optimization approach to the product sustainability, the mathematical model presented in this study considers direct costs proportional to the footprints. Future efforts can be made to explore the correlation between environmental aspects and indirectly related economic elements, as well as societal elements. It is also hoped that eventually, all major relations among the elements of the TBL can be built and analyzed via complex optimization models to represent the real world products.

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