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A new methodology for integration of end-of-life option determination and disassemblability analysis

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Abstract

Nowadays many countries have developed new legislations which are aimed at greater emphasis to force manufacturers to reuse, recycle, recover, and remanufacture their products at the end of their life. However, an essential process for the recycling and/or reuse/remanufacturing of end-of-life products is product disassembly. This entails large amounts of capital expenditure, and most manufacturers would not like to even consider disassembling and remanufacturing unless capital costs are justified and financial gains assured. To enhance the recycling process, it is necessary to analyze the product from the end-of-life point of view. Without the understanding of end-of-life aspect, the ease of disassembly and recycling of a product can hardly be enhanced. Therefore, there is a strong need for developing a new methodology to evaluate the product disassemblability aspect and to determine its technological and economic impact at the end-of-life. This paper presents a new methodology to fulfill the above needs. It integrates the end-of-life option determination and disassemblability evaluation in one framework. The proposed methodology is divided into five stages: (1) Define the product; (2) Determine the end-of-life option and calculate the end-of-life value; (3) Evaluate the disassemblability and calculate the disassembly cost; (4) Calculate the recycling rate; and (5) Disassembly evaluation report. In order to show the application of the proposed methodology, a case study was conducted. The results of the case study prove that the methodology is able to show how economically efficient is it to disassemble a product and identify the opportunity of a component to be reused and/or recycled/remanufactured.

Author keywords

Disassemblability; Disassembly; End-of-life; Recycling

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Editors

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Preface

"Treatise on Sustainability Science and Engineering" is aimed at bringing out the state-of-the-art developments in sustainability applications, including principles and practices developed and implemented across a wide spectrum of industry. This book presents a total of 18 chapters, authored by prominent researchers and application specialists in sustainability science and engineering, and these chapters are thematically assembled in the following four major parts:

Part I: Design for Sustainability (6 Chapters)
Part II: Sustainability Metrics and Analysis (4 Chapters)
Part III: Sustainable Energy (5 Chapters)
Part IV: Sustainable Supply/Value Chains (3 Chapters)

Part I introduces design for sustainability concepts, methodologies, principles, and practices through systematic studies in a total of six closely related chapters covering a range of models and design and application methodologies for sustainability, beginning with a "Life-Cycle Optimization Methods for Enhancing the Sustainability of Design and Policy Decisions" outlining and presenting life cycle optimization methods.

LCO developed for evaluating the optimal service life and asset management decisions from energy, emissions, costs, and policy issues. This LCO model is based on dynamic programming methods. Applications are drawn from automobiles and the household refrigerators and air conditioners, with trade-offs between utilizing the existing product models and replacing it with the more efficient newer one. This is followed by "Second Thoughts on Preferred End-of-Life Treatment Strategies for Consumer Products" providing further thoughts on new, preferred end-of-life strategies for consumer products which have, typically, lifetime extensions as preferred options to disassembly options for reuse and recycling. This priority hierarchy method was shown as too simplistic in the light of new technological advances involving the use of self-disassembly methods and business propositions, with research-driven case studies demonstrating the reversal of such traditional priority end-of-life options by emphasizing the viability of systematic product reuse, refurbishment or disassembly for reuse where material recycling was shown as the only realistic scenario. "A New Methodology for Integration of End-of-Life Option Determination and Disassemblability Analysis" in this part presents a new methodology for integrating the process of end-of-life determination with product disassembly decision methods by introducing a five-stage strategy: (1) product definition, (2) determination of end-of-life option with residual value calculation, (3) evaluation of disassembly methods with relevant cost analysis, (4) calculation of recycling costs, and (5) documentation of a disassembly report. A case study is presented to demonstrate the feasibility of this new methodology. "Sustainability Under Severe Uncertainty: A Probability-Bounds-Analysis-Based Approach" deals with an introduction of a probability bound analysis (PBA) method for handling uncertainties due to lack of and/or imprecise information on sustainability. The use of this method was shown as feasible for modeling the propagation of uncertainty through complex mathematical models in simulation and decision making. This is shown through a study of two different computational algorithms: Dependency Bound Convolution (DBC) for simple algebraic formulations, and the Black-Box Compatible (BBC) methods for complex models. "Life Cycle Assessment (LCA): A Means to Optimise the Structure of Sustainable Industry" in this part shows the Life Cycle Assessment (LCA) method as a means to optimize the structure of the sustainable industry by showing that sustainability will influence all aspects of industrial processes including the raw material base, size, and location of their interactions within and with the environment, and with the economic and social implications. A case study of first generation bioethanol processes is demonstrated to highlight such interactions. The last chapter in this part "Practical Approaches to Sustainability: iSUSTAIN® Tool for Green Chemistry Case Study" introduces a Green Chemistry Scoring Tool iSUSTAIN™. This tool is based on the 12 principles of green chemistry where metrics were developed for each tool to measure the sustainability contents of products and processes in terms of their inherent "greenness".

Part II presents a detailed sustainability metrics and analysis in four chapters. "Measuring Sustainability: Deriving Metrics from a Secure Human–Environment Relationship" presents a practical means for measuring sustainability in terms of developed metrics with minimum human adverse effects. It is promoted that the newly defined metrics must define the boundaries of human activities relative to environmental capabilities to offer some early warning signs of such conditions that would normally be unfavorable to human life, thus leading to an imposed change. "Science-Based Metrics for Product Sustainability Assessment" makes an attempt to present a framework for developing science-based metrics for evaluating product sustainability.

This chapter shows the recent NIST efforts in addressing the need for developing such metrics and tools for scientific evaluation of life cycle economic and environmental performance of products. The latter is shown to be measured using LCA methods that assess the "carbon footprint" of products, as well as 11 other sustainability metrics including fossil fuel depletion, smog, water use, habitat alteration, indoor air quality, and human health. These performance metrics are applied in the assessment of 230 building products within the NIST's Building Environmental and Economic and Sustainability (BEES) tool involving a BEES case study of five floor covering products. "Key Business Metrics that Drive Sustainability into the Organization" presents key business metrics that drive sustainability into the organizations based on the stakeholder context from the sustainability-related aspirations, goals, and challenges that are both internal and external to an organization. This chapter also introduces the GEMI *Metrics Navigator*™ process, a roadmap for identifying key sustainability issues, and business metrics, which are aimed at achieving the sustainability goals of an organization. The next chapter in this part "Environmental Assessment and Strategic Environmental Map Based on Footprints Assessment" presents a novel graphical representation using an environmental evaluation and strategic environmental map based on the various footprints such as carbon footprint, water footprint, energy footprint, emission footprint, work environment footprint, etc. This graphical method allows the use of these footprints with an additional dimension of cost.

Part III integrates five interrelated chapters in the major area of sustainable energy. This part begins with a "Exploring How Technology Growth Limits Impact Optimal Carbon Dioxide Mitigation Pathways" showing how technology growth can limit impact optimal carbon dioxide (CO_2) mitigation pathways. In this chapter, alternative growth bounds on wind and solar power, nuclear power, and CO_2 sequestration are examined for a hypothetical greenhouse gas (GHG) mitigation scenario. A nested parametric sensitivity analysis is used to examine the response to individual and combinations of bounds. Both, modeling and planning perspectives are shown. "Nanoscale Engineering Approach for Enhancing the Performance of Photovoltaic Cell Technologies for Non-Fossil Energy Sources" presents a specific nanoscale engineering approach for enhancing the performance of photovoltaic (PV) cell technologies for the use of non-fossil energy sources. Two emerging technologies, PV cells and concentrated solar power (CSP) are shown as capable of delivering the large portion of United States' energy needs in the next 40 years if they are properly developed. In this chapter, first, fundamental mechanisms of how electricity is generated by these two technologies are described. Next, recent developments in the application of nanotechnology for enhancing PV cell performance are presented. This chapter shows a nanoscale engineering approach for developing device designs that would counter the two limiting factors. "Sustainable Mobility: Insights from a Global Energy Model" presents sustainable mobility insights from a global energy model that includes a detailed description of light-duty vehicle and fuel technologies, used to investigate cost-effective light-duty vehicle/fuel technologies in a carbon-constrained world. Three conclusions emerged from this chapter. First, there is no "silver bullet" vehicle or fuel technology. Second, a multisector perspective is needed when addressing greenhouse gas emissions. Third, alternative fuels are needed in response to the expected dwindling oil and natural gas supply potential by the end of the century. "Life-Cycle Analysis of Biofuels and Electricity for Transportation Use" presents a LCA of biofuels and electricity for transportation use. This chapter shows that the transportation sector has been relying solely on petroleum, consuming more than 50 % of the global world oil production, with the United States being the top oil-importer country. Two major issues facing the transportation sector in the U.S. and other major countries are shown: energy security and environmental sustainability. It was shown that improvements in the energy efficiency of vehicles and the substitution of petroleum fuels with alternative fuels can help to slow the growth in the demand for petroleum oil and mitigate the increase in greenhouse gas emissions. Biofuels and electricity are known for their potential reduction of petroleum use and greenhouse gas emissions. This chapter examines the potential reduction of life cycle energy use and greenhouse gas emissions associated with the use of biofuels in internal combustion engine vehicles and electricity in plug-in hybrid electric vehicles and battery-powered electric vehicles. The last chapter in this part "Liquid Biofuels: We Lose More Than We Win" shows a critical scenario where biomass, according to the world trends, is shown as a priority resource for fossil fuel substitution, and that biomass is increasingly used for both the transport and the heat and power sectors, with increasing interest in using it for chemical production as well. The chapter shows that as the magnitude of biomass, that is or can be made available for energy purposes, is small compared to the magnitude of the new potential customers for it, any long-term and large-scale prioritization of biomass for one purpose will imply a loss of alternative uses of the same biomass. If the lost alternatives are, then, significantly more efficient as well as economically more attractive in fossil fuels substitution and CO_2 reduction, we lose more than we win. The authors claim that this is the case for most liquid biofuels, including first generation biodiesels (plant biodiesels) as well as first and second generation bioethanols produced in Europe and the USA.

Part IV presents three interesting chapters on sustainable supply chains, with the opening chapter "Meeting the Challenge of Sustainable Supply Chain Management" showing that assessing and improving the sustainability of products and services requires a life cycle approach, consideration of the complete supply chain, and examination of the role of consumption as the driver for production. It is shown that the economic and environmental dimensions can be explored by integrating value chain analysis (VCA) and LCA to show the distribution of economic benefits and environmental impacts along the supply chain. Environmental intensities (i.e., impact per unit of added value) are shown as frequently high for material extraction and refining, and reduce progressively along the supply chain through manufacturing and distribution. Incorporating consideration of social equity in analysis of supply chains was shown to require further methodological development involving a "soft system" analysis to complement the "hard system" approaches of VCA and LCA. From the consumption perspective, it is shown that sustainable development requires not only reduction in the environmental intensity of products and services, but also more equitable distribution of economic and social benefits along the supply chain. "Sustainable Consumption and Production: Quality, Luxury and Supply Chain Equity" shows that the pressures of social and environmental responsibility require companies to consider sustainability issues across the full product life cycle, from the conduct of upstream suppliers to the disposition of obsolete products. In this regard, leading companies are shown to be adopting a variety of sustainable business practices that reduce their supply chain footprint while generating increased value for stakeholders. Systems thinking and life cycle management are shown as key elements in achieving measurable improvements in sustainability and profitability. The author shows that the incremental supply chain efficiency improvements are insufficient to slow the increases in carbon emissions and other adverse ecological impacts and collaboration is urged among progressive multinational companies with governments and nongovernmental organizations to enable decoupling of material flows from the economic value creation. "Transforming Supply Chains to Create Sustainable Value for All Stakeholders" presents the need for sustainable value creation by showing that promoting sustainability in business operations requires that products, processes as well as the entire supply chain (the system), is designed and operated by taking account of not only economic benefits, but also environmental and societal implications. The chapter presents that from a supply chain perspective, economic value added (EVA) has long been used as a measure to evaluate supply chain performance. This chapter presents the concept of sustainable value creation and why the scope of conventional supply chain management processes must be broadened to generate sustainable value. This chapter offers a discussion of successful and disastrous case examples.

Overall, the four parts of this proposed book-volume are filled with closely knitted, carefully chosen, and interacting 18 chapters of significant state-of-the-art work. All chapters have been peer-reviewed and revised accordingly. We sincerely thank all reviewers who carefully reviewed the chapters and provided valuable comments for revision. This edited book would add significant values to the readers in the domain of sustainability science and engineering. Researchers in academic and industrial organizations, technical and managerial staff from companies, and staff from governmental organization would benefit from the collection this work, which is aimed at advancing the current state-of-the-art into next level for greater societal benefits.

The authors and co-authors of all chapters deserve credit for their excellent contributions and timely actions on various aspects of the production of this book. We also sincerely thank the two graduate students at the University of Kentucky, Tao Lu and Chris Stovall for their hard work in carefully proofreading all finally updated chapters, and for working with all authors of chapters in completing documentation needed for the publication of this book. We also thank the publishers for their support and help in publishing this book.

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I.S. Jawahir
S.K. Sikdar
Y. Huang

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Treatise on Sustainability Science and Engineering

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- (view affiliations)

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Benefits

- Provides important insights into sustainability metrics
- Contributes to the growing interest in life cycle assessment
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- Offers a wide spectrum of research on sustainability science and engineering

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- Design for sustainability
- Sustainability metrics and analysis
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Significant, state-of-the-art work, methodologies, practices and plans are presented by researchers, technology developers and industry leaders. Topics discussed include:

- Life cycle assessment
- Product end-of-life options
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The uniqueness of this book lies in the range of topics covered with in-depth analysis and case studies.

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Keywords

Life Cycle Assessment Supply Chains Sustainability Metrics Sustainability Science Sustainable Energy

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by Feri Afrinaldi

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A New Methodology for Integration of End-of-Life Option Determination and Disassemblability Analysis

Feri Afrinaldi, Muhamad Zameri Mat Saman and Awalluddin Mohamad Shaharoun

Abstract Nowadays many countries have developed new legislations which are aimed at greater emphasis to force manufacturers to reuse, recycle, recover, and remanufacture their products at the end of their life. However, an essential process for the recycling and/or reuse/remanufacturing of end-of-life products is product disassembly. This entails large amounts of capital expenditure, and most manufacturers would not like to even consider disassembling and remanufacturing unless capital costs are justified and financial gains assured. To enhance the recycling process, it is necessary to analyze the product from the end-of-life point of view. Without the understanding of end-of-life aspect, the ease of disassembly and recycling of a product can hardly be enhanced. Therefore, there is a strong need for developing a new methodology to evaluate the product disassemblability aspect and to determine its technological and economic impact at the end-of-life. This paper presents a new methodology to fulfill the above needs. It integrates the end-of-life option determination and disassemblability evaluation in one framework. The proposed methodology is divided into five stages: (1) Define the product; (2) Determine the end-of-life option and calculate the end-of-life value; (3) Evaluate the disassemblability and calculate the disassembly cost; (4) Calculate the recycling rate; and (5) Disassemblability evaluation report. In order to show the application of the proposed methodology, a case study was conducted. The results of the case study prove that the methodology is able to show how economically efficient is it to disassemble a product and identify the opportunity of a component to be reused and/or recycled/remanufactured.

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Keywords Disassembly · Disassemblability · End-of-life · Recycling

1 Introduction

Laws in European Union, Japan, USA, and Australia require manufacturers to take back their products at the end of their useful life and recycle them. It is caused by the tremendous growth in the demand for consumer products that have a shortened lifespan compared with other products. At present, approximately 75–80 % of end-of-life vehicles in terms of weight, mostly metallic fractions, both ferrous and non ferrous are being recycled. The remaining 20–25 % in weight, consisting mainly of heterogeneous mix of materials such as resins, rubber, glass, textile, etc., is still being disposed (Toyota Motor Company 2005; The European Parliament and the Council of European Union 2000). In the case of electronic products, US Environmental Protection Agency (EPA), estimates about 40 million computers became obsolete in a year and only 18 % of them are recycled, the rests are still disposed of, primarily in landfills (EPA 2008). However, the number of landfills for disposal of end-of-life products has seen an exponential decrease (Desai 2002).

According to European Parliament and Council of European Union (2000, 2003a, b), requirements for recycling the end-of-life products and their components should be integrated in the design and development of new products. Manufacturers should ensure that products are designed and manufactured in such a way as to allow to quantified targets for reuse, recycle, and recovery to be achieved. Product manufacturers must endeavor to reduce the use of hazardous substances when designing products and increase the use of recycled materials in product manufacture.

Based on Desai (2002), before end-of-life products can be recycled, end-of-life disassembly mechanisms need to be in place. According to Kwak et al. (2009), to enhance the recycling process, it is necessary to analyze the product from the end-of-life point of view, without the understanding of end-of-life aspect, the ease of disassembly and recycling of a product can hardly be enhanced. Results of this analysis process will show how economically efficient it is to disassemble a product and identify the opportunity of a component to be recycled. This paper proposed a new methodology which integrates end-of-life option determination and disassemblability evaluation to assess the design of products for their technical and economic viability at end-of-life.

2 Related Study

2.1 End-of-Life Concept

According to the Rose et al. (2000), end-of-life is the point in time when the product no longer satisfies the initial purchaser or first user. When a product reaches its end-of-life, it can be reused, remanufactured, recycled (primary or secondary), incinerated, or dumped in a landfill (Lee et al. 2001).

A bulk of research has been conducted to aid the product designers to select the appropriate end-of-life option of their product. Muller (1999) proposed a methodology to estimate end-of-life cost. The first step in this method is to analyze the end-of-life recycling. According to the author, it should be done by recycling experts. Rose et al. (2000) proposed End-of-Life Design Advisor to guide product developers to specify the appropriate end-of-life option based on the product characteristics. Rose and Stevels (2001) presented End-of-Life Strategy Environmental Impact Model. The environmental considerations are a factor that is considered in this method. A combination with product characteristics and cost analyses will make these methods more beneficial. Lye et al. (2002) designed Environmental Component Design Evaluation. It uses Analytical Hierarchy Process to compare criteria in assessing the environmental impact of a product. One of the criteria is end-of-life value. Lee et al. (2001) proposed a complete guideline for determining a feasible end-of-life option. The guideline was developed based on the material composition of the component. The decision to recycle (primary and secondary), dump to the landfill, or to handle with special means is made based on the material composition. The decision to reuse or remanufacture requires foreknowledge of the component manufacturing process undergone by the component, and its condition at the end-of-life. The decision can only be made by human intervention. For every option taken, the authors also proposed a method to calculate the end-of-life value of the product.

2.2 Design for Disassembly

Desai and Mital (2005) defined disassembly, in the engineering context, as an organized process of taking apart a systematically assembled product (assembly of components). Products may be disassembled to enable maintenance, enhance serviceability, and/or to affect end-of-life objectives such as product reuse, remanufacture, and recycling.

Design for disassembly focuses on design efforts in order to improve the performance of a product with attention given to separation and sorting of waste in an effort to enhance the easiness of disassembly for product maintenance and/or end-of-life treatments (Jovane et al. 1993; Takeuchi and Saitou 2005). Based on the method for disassembly, disassembly process may clearly be split into two categories: destructive disassembly and non-destructive disassembly (Desai and Mital 2005).

Based on Mok et al. (1997), disassemblability is defined as the degree of easiness disassembly. Desai and Mital (2003) stated that use of force, mechanism of disassembly, use of tools, repetition of parts, recognizability of disassembly points, product structure, and use of toxic materials affect disassemblability.

Various methodologies have been developed to evaluate disassemblability of a product.

McGlothlin and Kroll (1995) designed a spread sheet-like chart to measure the ease of disassembly of a product. The authors measured the disassembly difficulties based on accessibility, positioning of tool, amount of force required to perform the disassembly task, time, and special (this is a provision to note special problems encountered that do not fit in any of other categories). Suga et al. (1996) proposed a method to evaluate disassembly evaluation by introducing two parameters, energy for disassembly and entropy for disassembly. Energy for disassembly is energy required to disconnect an interconnection and calculated for mechanical fasteners such as screw (release energy) and snap fit (elastic deformation energy). The concept of entropy for disassembly is based on idea that degree of difficulty of a disassembly depends on how many methods were used to make interconnections, as well as the number of different directions necessary to complete all disassembly operations.

Kroll and Hanft (1998) and Kroll and Carver (1999) presented a method for evaluating ease of disassembly of a product, proposed a catalog of task difficulty scores, and explained the derivation of difficulty scores. The method presented used a spreadsheet-like chart and a catalog of task difficulty scores. The scores are derived from work-measurement analyses of standard disassembly tasks. Yi et al. (2003) proposed a method for evaluating disassembly time. The aim of this method was to obtain an approximate disassembly time for the product to be disassembled by using a formula derived from information on the product's connecting parts without disassembling the product directly. In this method, authors divided disassembly time into preparation time, moving time, disassembly time, and postprocessing time. It is called as the base time. Each base time is influenced by factor time.

Desai and Mital (2005) presented a methodology to design products for disassembly. It would facilitate the end-of-life product disassembly with a view to maximize material usage in the supply chain at a reduced environmental effect. According to this, disassemblability of product is a function of several factors, such as effective tools placement, weight, size, material, and shape of the component being disassembled. The proposed methodology consists of two elements, a scoring system to evaluate the disassemblability and the systematic application of design for disassembly. In order to measure the disassembly time, the authors only focus on the operations which directly affect the disassembly efficiency. Design attributes and design parameters are provided in aiding the designers in selecting the disassembly score. The ergonomic considerations are also involved in developing the score. It is proposed for the high volume disassembly operations.

3 Proposed Methodology

The proposed methodology can be derived into five phases as shown in Fig. 1.

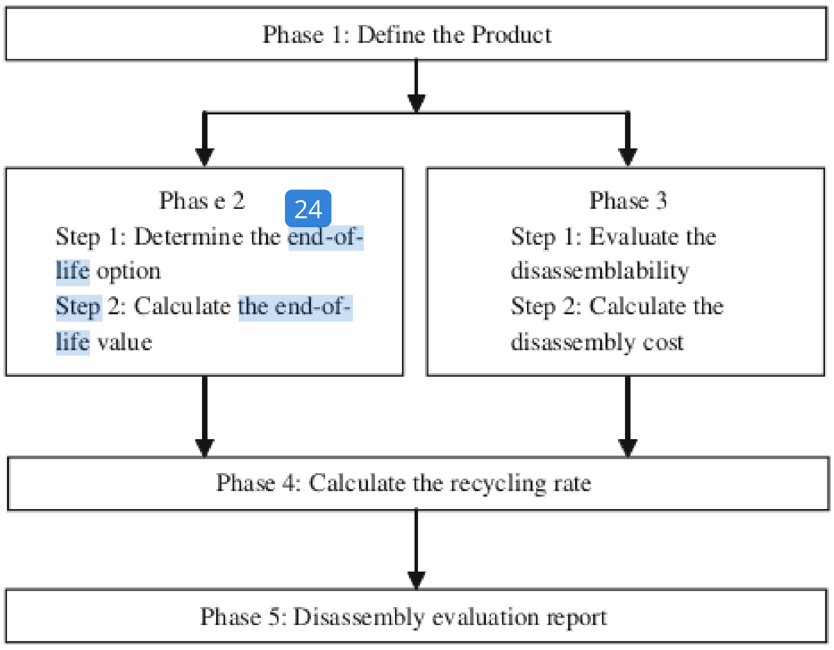

Fig. 1 Proposed methodology

3.1 Phase 1 Define the Product

Define the product means obtaining the type and quantity of fasteners among product's component, mass of subassemblies or components, materials used in subassemblies, and product's component and disassembly tasks required to take apart the components from subassemblies or product.

Connection information provides information about the construction of product and has a great significance in the application of materials not compatible with one another for recycling (Brouwers and Stevels 1995; BMW Group 2002). Material information is needed to calculate the costs or revenues of material for upgrading or for disposal. Mass of the product's parts is needed to calculate end-of-life processing costs and to calculate the revenues or costs of materials for upgrading or for disposal.

3.2 Phase 2 Determine the End-of-Life Option and Calculate the End-of-Life Value

There are two steps involved in phase two, the end-of-life option determination and the end-of-life value calculation.

3.2.1 Step 1 Determine the End-of-Life Option

The most appropriate end-of-life option often depends on the nature of components in the product (Lee et al. 2001). In this work, the choosing of end-of-life options is based on the quality of end-of-life components and their material composition. The quality of components will be used to determine that the components will be reused or remanufactured, if the components are not appropriate to be reused or remanufactured so their material composition will be used to determine which options are more appropriate, recycled (primary or secondary recycling), incinerated, dumped to landfill, or specially handled (for toxic material). The method proposed in Lee et al. (2001) is adopted. If the component:

1. Is made from metal without any other alloy, primary recycling is recommended. If alloys are present, they alter the mechanical properties of the parent metal, so secondary recycling or landfill is more appropriate.
2. Is polymeric, primary recycling is recommended otherwise consider secondary recycling or incineration to recover its energy content.
3. Is made from ceramic, secondary recycling or landfill is recommended.
4. Is made from an elastomeric or is a composite material, secondary recycling or incineration is recommended, otherwise landfill.
5. Contains toxic or hazardous material, special handling is required.

3.2.2 Step 2 Calculate the End-of-Life Value

Because the proposed methodology is addressed to evaluate disassembly operation at the design stage of products so that all costs required in calculating end-of-life value must be forecasted for t period of time, where t is the estimated age of product. After end-of-life value is determined, this value is then converted to the present value amount. It is used to compare end-of-life value with design or redesign cost.

In order to estimate end-of-life cost, linear, logarithmic, exponential and power regression models are used, as shown in Eqs. (1–4) and least–square method is used to estimate $\hat{\beta}_0$ and $\hat{\beta}_1$.

$$\text{Cost} = \hat{\beta}_0 + \hat{\beta}_1 \; t \tag{1}$$

$$\text{Cost} = \hat{\beta}_0 + \hat{\beta}_1 \; \ln(t) \tag{2}$$

$$\text{Cost} = \hat{\beta}_0 \; e^{\hat{\beta}_1 \; t} \tag{3}$$

$$\text{Cost} = \hat{\beta}_0 \; e^{\hat{\beta}_1 \; t} \tag{4}$$

The Present value of each end-of-life cost is calculated by using Eq. (5).

$$PV = C_t \times \frac{1}{(1+d)^t} \tag{5}$$

where

PV Present value
C_t Future cost at the t time period
d Discount rate
t Life of the product (year).

Equations (6–13) are used to calculate end-of-life value of each component Lee et al. 2001. All costs which are required to calculate the end-of-life value are in the present value amount.

$$\text{Reuse value} = \text{Cost of component (\$)} - \text{Miscellaneous (\$)} \tag{6}$$

$$\begin{aligned}\text{Remanufacture value} = {} & \text{Cost of component (\$)} - \text{Remanufacture Cost (\$)} \\ & - \text{Miscellaneous cost (\$)}\end{aligned} \tag{7}$$

$$\begin{aligned}\text{Primary recycle value} = {} & \text{Weight of component (kg)} \times \text{Market value of material (\$/kg)} \\ & - \text{Miscellaneous cost (\$)}\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Secondary recycle value} = {} & \text{Weight of component (kg)} \times \text{Scrap value of material (\$/kg)} \\ & - \text{Miscellaneous cost(\$)}\end{aligned} \tag{9}$$

$$\begin{aligned}\text{Incinerate value} = {} & \text{Energy produced (KJ)} \times \text{Unit of energy (\$/KJ)} \\ & - \text{Miscellaneous cost}\end{aligned} \tag{10}$$

$$\begin{aligned}\text{Landfill cost} = {} & -(\text{Weight of component (kg)} \times \text{Cost of landfill (\$/kg)}) \\ & - \text{Miscellaneous cost (\$)}\end{aligned} \tag{11}$$

$$\begin{aligned}\text{Special handing cost} = {} & -(\text{Weight of component (kg)} \times \text{Cost of special handling (\$/kg)}) \\ & - \text{Miscellaneous cost (\$)}\end{aligned} \tag{12}$$

$$\text{Miscellaneous cost} = \text{Handling} + \text{Transportation} + \text{Storage} + \text{Re-processing} \tag{13}$$

3.3 Phase 3 Evaluate the Disassemblability and Calculate Disassembly Cost

There are two steps involved in phase 3, the evaluation of disassemblability and the calculation of disassembly cost.

3.3.1 Step 1 Evaluate the Disassemblability

The evaluation method used in this research is disassemblability evaluation method proposed by Desai and Mital (2005). Desai and Mital (2005) subdivide the disassembly operation into the basic element tasks. As an example, a simple unscrew operation that may be subdivided into the following tasks (Desai and Mital 2005):

1. Constrain the product to prevent motion during disassembly.
2. Reach for tool (power screwdriver).
3. Grasp the tool.
4. Position the tool (accessibility of fastener).
5. Align the tool for commencement of operation (accessibility of fastener).
6. Perform disassembly (unscrew operation: force exertions in case of manual unscrew operation).
7. Put away the tool.
8. Remove screws and place them in a bin.
9. Remove the component and put it in a bin.

According to Desai and Mital (2005), task numbers 4, 5, 6, and 9 actually affect disassembly. Task numbers 1, 2, and 3 are preparatory tasks. Assuming operator dexterity, speed of operation, weight and size of tool, and workplace conditions remain constant, altering the preparatory tasks would have no effect on the efficiency of the disassembly process. Otherwise, the efficiency of the disassembly process can be directly attributed to task numbers 4, 5, 6, and 9. Task numbers 4, 5, 6, and 9 are directly affected by the design configuration of the product. For example, task number 9, the removal of the component is influenced by size, shape, weight, and material of the component. According to Desai and Mital (2005), large, unsymmetrical, and heavy components as well as small and sharp components are difficult to handle, and finally result in decrease in disassembly efficiency. Moreover, according to Desai and Mital (2005) if a large number of the above tasks are to be performed during the work shift (frequency of operations) and the worker is forced to adopt an unnatural posture resulting in the onset of static fatigue, the long-term effects can be devastating. Based on these, Desai and Mital (2005), address the following parameters as the parameters affecting the disassemblability:

1. Degree of accessibility of components and fasteners.
2. Amount of force (or torque) required for disengaging components (in case of snap fits) or unfastening fasteners.
3. Positioning.
4. Requirements of tools.
5. Design factors such as weight, shape and size of components being disassembled.

In order to determine the disassemblability score, Desai and Mital (2005) apply the Method Time Measurement (MTM) system. The simplest disassembly task of removing an easily grasped object without the exertion of much force by hand by a trained worker under average conditions has been considered as the basic disassembly task. A score of 73 TMUs was assigned to this task, which corresponded to time duration of approximately 2 s. Subsequent scores were assigned based on the detailed study of most commonly encountered disassembly operations. Table 1 shows the scoring system of numeric analysis of disassemblability.

3.3.2 Step 2 Calculate Disassembly Cost

The calculation of the disassembly cost is based on the disassembly operation rate per unit of time. Multiplying this rate with the disassembly time for each operation will result in the disassembly cost for each disassembly operation.

Disassembly time and disassembly cost for each task are defined as in Eqs. (14) and (15) (Desai and Mital 2005; Lambert and Gupta 2005)

$$\text{Disassembly time(in second)} = \text{Total disassembly score} \times 10 \times 0.036\,\text{s} \quad (14)$$

$$\begin{aligned}\text{Disassembly cost(\$)} &= \text{Disassembly time (second)} \\ &\quad \times \text{Disassembly cost (\$/second)}.\end{aligned} \quad (15)$$

3.4 Phase 4 Calculate Recycling Rate

To measure that current design meets or does not meet end-of-life directive in terms of the amount of material or parts that can be recycled, recyclability is used as the indicator. Based on the Manual for Recycling-Optimized Product Development (Lambert and Gupta 2005), the recycling rate is defined as:

$$R_Q = \frac{M_{R1} + M_{R2}}{M_G} \times 100\,\% \quad (16)$$

M_{R1}, M_{R2} Mass (kg) of materials in components in recycling rate categories R1 and R2.

M_G Mass (kg) of product or subassembly.

Table 1 Scoring system of numeric analysis of disassemblability (Desai and Mital 2005)

Design attribute	Design feature	Design parameters	Score	Interpretation
Disassembly force	Straight line motion without exertion of pressure	Push/pull operations with hand	0.5	Little effort required
			1	Moderate effort required
			3	Large amount of effort required
	Straight line and twisting motion without pressure	Twisting and push/pull operations with hand	1	Little effort required
			2	Moderate effort required
			4	Large amount of effort required
	Straight line motion with exertion of pressure	Inter-surface friction and/or wedging	2.5	Little effort required
			3	Moderate effort required
			5	Large amount of effort required
	Straight line and twisting motions with exertion of pressure	Inter-surface friction and/or wedging	3	Little effort required
			3.5	Moderate effort required
			5.5	Large amount of effort required
	Twisting motions with pressure exertion	Material stiffness	3	Little effort required
			4.5	Moderate effort required
			6.5	Large amount of effort required
Material handling	Component size	Component dimensions (very large or very small)	2	Easily grasped
			3.5	Moderately difficult to grasp
			4	Difficult to grasp
		Magnitude of weight	2	Light (<7.5 lb)
			2.5	Moderately heavy (<17.5 lb)
			3	Very heavy (<27.5 lb)
	Component symmetry	Symmetric components are easy to handle	0.8	Light and symmetric
			1.2	Light and semi-symmetric
			1.4	Light and asymmetric
			2	Moderately heavy, symmetric
			2.2	Moderately heavy, semi-symmetric
			2.4	Moderately heavy, asymmetric
			4.4	Heavy and symmetric
			4.6	Heavy and semi-symmetric
			5	Heavy and asymmetric
Requirement of tools for disassembly	Exertion of force		1	No tools required
			2	Common tools required
			3	Specialized tools required
	Exertion of torque		1	No tools required
			2	Common tools required
			3	Specialized tools required

(continued)

Table 1 (continued)

Design attribute	Design feature	Design parameters	Score	Interpretation
Accessibility of joints/grooves	Dimensions	Length, breadth, depth, radius, angle made with surface	1	Shallow and broad fastener recesses, large and readily visible slot/recess in case of snap fits
			1.6	Deep and narrow fastener recesses, obscure slot/recess in case of snap fits
			2	Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate
	Location	On plane surface	1	Groove location allows easy access
		On angular surface	1.6	Groove location is difficult to access. Some manipulation required
		In a slot	2	Groove location very difficult to access
Positioning	Level of accuracy required to position the tool	Symmetry	1.2	No accuracy required
			2	Some accuracy required
			5	High accuracy required
		Asymmetry	1.6	No accuracy required
			2.5	Some accuracy required
			5.5	High accuracy required

Recycling categories (R1, R2, and R3) are defined as:

1. *R1* Component suitable for economic recycling with Suitability for Recycling $\geq 100\ \%$.
2. *R2* Component suitable for economic recycling which has $80\ \% \leq$ Suitability for Recycling $< 100\ \%$.
3. *R3* Not suitable for economic recycling with Suitability for Recycling $< 80\ \%$.

Suitability for recycling is calculated as follows:

$$\text{Suitability for recycling} = \frac{\text{Cost (equivalent new material + disposal)}}{\text{Cost (dismantling + re-processing + logistics)}} \times 100\,\% \tag{17}$$

Dismantling cost means disassembly cost and re-processing cost means cost required for upgrading the components based on its end-of-life option.

3.5 Phase 5 Disassemblability Evaluation Report

In order to provide reports that can be used to make recommendation regarding improvement potentials, this methodology provides three potential improvements:

1. Improvement of product structure
   Based on the results of the numeric evaluation of disassemblability and end-of-life value for each component, a portfolio of disassembly time versus profit of single components gives a quick overview of weak points in the product structure. All components with high end-of-life profit and long disassembly time and all components with low end-of-life profit and short disassembly time have potential to be improved by repositioning them in the product hierarchy or by changing their joining technique.
2. Improvement of ease of disassembly
   By using disassemblability evaluation scores the designer also can identify which parameter of disassemblability has the highest contribution to the difficulties of the disassembly operation for a particular component. It shows the weaknesses of the design and it can be used as basis to suggest feasible design alternatives.
3. Improvement of material content
   Suitability for recycling and recycling rate indicates that current materials used are suitable or not for recycling in terms of economic consideration.

4 Assumption

The application of the above methodology is limited by several assumptions:

1. In computing the end-of-life value it is assumed that the recycling facility has 100 % efficiency.
2. The disassembly cost is assumed as the labor cost per unit of time.
3. As mentioned earlier that MTM System was used in estimating the disassembly time. Here, in using this method, it is assumed that the disassembly operations are performed sitting down at the bench level.
4. The operators doing the disassembly operations are assumed to have average skill and work in the normal condition.
5. The material of the components developing the product is known.

5 Case Study and Results

In order to illustrate the application of the proposed methodology, a hair clipper is used as a case study. The purposes of this case study are to measure the disassemblability, estimate the disassembly time, and compute the recyclability of the hair clipper. Hair clipper which is being analyzed consists of 13 main components. The detailed information about the hair clipper is shown in Fig. 2.

In Phase 1, the type and quantity of fasteners among hair clipper's component, mass of the components, materials used, and disassembly tasks required to take apart the components from the product are obtained. There are two types of fasteners used in the hair clipper, screw and snap fit. Screws are released by unscrewing them and snap fits are released by pulling them.

In Phase 2, the end-of-life option for the components is obtained and the end-of-life value is calculated. The end-of-life option determination is based on the guideline proposed by Lee et al. (2001). In order to calculate the end-of-life value, Eqs. (6–13) are used. The result of the end-of-life option determination and the calculation of the end-of-life value are shown in Table 2.

As an illustration, lower cutter is discussed. Based on the proposed methodology, feasible end-of-life option for sheet metal is primary recycling. The Market value of metal is 1.54 \$/kg. Since miscellaneous costs are outside control of the designers, they are omitted from calculation. So,

$$\begin{aligned}\text{Primary recycling value} &= \text{Weight of component (kg)} \times \text{Market value of material (\$/kg)} \\ &\quad - \text{Miscellaneous cost (\$)} = 0.027\,\text{kg} \times 1.54\,\$/\text{kg} = \$0.04158.\end{aligned}$$

Table 2 shows that all components of the hair clipper give rise to a surplus and do not adversely impact the environment. A component which adversely impacts the environment will require special handling and the deficit incurred by special handling is indicated by the negative sign of the end-of-life value.

In Phase 3, the disassemblability is evaluated and then the disassembly cost is calculated. The scoring system proposed by Desai and Mital (2005) is applied. Table 3 shows numerical disassemblability analysis of unscrews operation for disassembling lower cutter and the calculation of disassembly cost in performing

Fig. 2 Hair clipper. *1* Low cutter, *2* Upper cutter, *3* Tip, *4* Handle, *5* U-shape, *6* Upper cover, *7* Front part, *8* Magnet, *9* Coil, *10* Outer switch, *11* Inner switch, *12* Cable, *13* Lower cover

Table 2 End-of-life option, disassemblability and recyclability evaluation result

Number	Component	Task	Mass (kg)	Material	EOL option	EOL value ($)	Suitability for recycling (%)	Disassembly time (second)
1	Lower cutter	Unscrew	0.027	Sheet Metal	PR	0.04158	230.77	9.36
2	Upper cutter	Pull	0.008	Sheet Metal	PR	0.01232	187.13	3.42
3	Tip	Pull	0.0005	Polypropylene	SR	0.00001	0.58	3.42
4	Handle	Unscrew	0.002	Polypropylene	SR	0.00004	1.59	5.04
5	U-shape	Pull	0.008	Sheet Metal	PR	0.01232	187.13	3.42
6	Upper cover	Unscrew	0.021	Polypropylene	SR	0.00042	4.49	18.72
7	Front part	Unscrew	0.002	Sheet Metal	PR	0.00308	17.09	9.36
8	Magnet	Pull	0.027	Metal	PR	0.04158	521.73	4.14
9	Coil	Unscrew	0.154	Cooper	PR	0.23716	1316.24	9.36
10	Outer switch	Pull	0.001	Polypropylene	SR	0.00002	1.17	3.42
11	Inner switch	Pull	0.004	Polypropylene	SR	8×10^{-5}	4.68	3.42
12	Cable	Pull	0.08	Cooper	PR	0.1232	1693.12	3.78
13	Lower cover	Pull	0.045	Polypropylene	SR	0.0009	47.62	3.78

Note EOL End-of-Life, *PR* Primary Recycling, and *SR* Secondary Recycling

Table 3 Disassembly time computation of lower cutter

Design attribute	Design attribute/parameter	Score
Force	Straight line and twisting motions with exertion of pressure/inter-surface friction and/or wedging	3
Material handling	Component dimensions	2
	Magnitude of weight	2
	Symmetric components are easy to handle	0.8
Requirement of tools	Exertion of torque	2
Accessibility	Dimensions/length, breadth, depth, radius, angle made with surface	1
	Location/on-plane surface	1
Positioning	Symmetry	1.2
Total		13

Disassembly time = number of screws × Total × 10 × 0.036 = 2 × 13 × 10 × 0.036 = 9.36 s
Disassembly cost = Disassembly time (second) × Labor cost ($/second) = 9.36 × 0.002 = $0.01872

the unscrew operation. Lower cutter has two identical screws which have to be removed so that the disassembly time of the door gear is 2 × 13 × 10 × 0.036 = 9.36 s. The labor cost is $0.002/s, so that Disassembly cost = 0.002 × 9.36 = $0.01872.

Table 3 shows the numerical disassemblability analysis of unscrews operation for disassembling the lower cutter which has two screws. From Table 3, it can be seen that force as the design attribute or parameter of design has the highest contribution to the duration of disassembly time of lower cutter. In order to reduce the exertion of force required to disengage the lower cutter, according to Desai and Mital (2005), appropriate materials for component bearing surfaces and/or fasteners should be selected to reduce inter-surface friction. Besides that the holding surfaces in component also needed to be redesigned. Developed software also provides redesign recommendations in order to increase the disassemblability of the product analyzed.

In Phase 4, recycling rate is determined. Before recycling rate can be calculated, Suitability for Recycling must be calculated earlier. As an example, suitability for recycling of lower cutter is explained. Cost of equivalent new material = mass (kg) × cost of equivalent new material of lower cutter ($/kg) = 0.027 × 1.54 = $0.04158, disposal cost = mass (kg) × disposal cost per kg ($/kg) = 0.027 × 0.06 = $0.00162, dismantling cost = disassembly time (second) × disassembly rate ($/second) = 9.36 × 0.002 = $0.01872, re-processing cost and logistic cost are omitted from the calculation because they are outside control of the designers. Then,

$$\text{Suitability for Recycling} = [(0.04158 + 0.00162)/0.01872] \times 100\,\% = 230.77\,\%.$$

Table 2 also shows Suitability for Recycling of all components of hair clipper. Based on recycling category of each component, recycling rate can be calculated. Total mass of hair clipper is 0.3795 kg and total mass of the components with R1 and R2 categories is 0.304 kg. Therefore,

$$\text{Recycling rate} = (0.304/0.3795) \times 100\,\% = 80.1\,\%$$

Based on the suitability recycling, lower cutter's suitability for recycling is 230.77 %, it means that if lower cutter is not recycled the total cost of new material for producing a new lower cutter plus cost required disposing the end-of-life lower cutter is 2.3077 times as much as total costs (disassembly, reconditioning and logistic) required if it is recycled. Based on this, it is better if lower cutter is recycled. Table 2 presents suitability for recycling of all components of hair clipper. The recycling rate calculation indicates that 80.1 % (in terms of weight) out of all materials used in the hair clipper can be recycled at feasible and reasonable expenditure.

In Phase 5, in order to show which components are having the potential to be redesigned, the portfolio of end-of-life value versus disassembly time and value return for removing component are provided, as shown in Figs. 3 and 4 respectively. Value return of removing is the ratio between end-of-life value and disassembly time of a component.

Based on Fig. 3, coil and upper cover have potential to be improved. These components have a high and low end-of-life values. They should be disassembled very easily. It can be solved by changing the joining technique or by repositioning

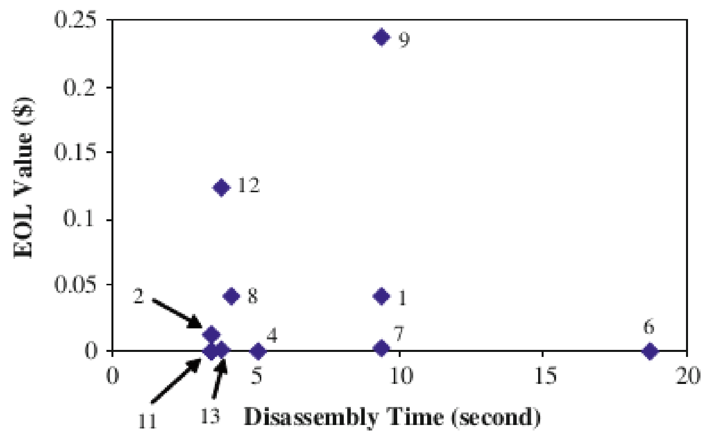

Fig. 3 End-of-life values versus disassembly time

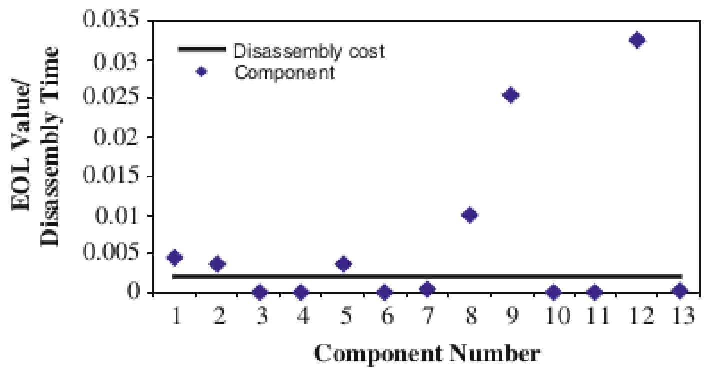

Fig. 4 Return value of removing components

them in the product hierarchy. Based on Fig. 4, tip, handle, upper cover, outer switch, and inner switch are uneconomical to disassemble because their return value of removing is lower than the disassembly cost.

6 Discussion

This work integrated the two aspects of the end-of-life disassemblability and recyclability analysis in one framework. Those aspects are end-of-life option determination and disassemblability analysis. Those aspects are required to be analyzed to compromise the requirements of the legislation to take back and recycle the end-of-life product and the cost incurred for taking back, disassembling, and re-processing the end-of-life product.

The end-of-life option determination will guide the designers to choose the appropriate end-of-life option of a vehicle. The guideline was developed based on the material composition and condition of the end-of-life vehicle's component. The decision to recycle (primary and secondary), dump to the landfill, or special handling is made based on the material composition. The decision to reuse or remanufacture requires foreknowledge of the manufacturing process undergone by the component, and its condition at the end-of-life, the decision can only be made by human intervention.

For each end-of-life option the end-of-life value is computed. The end-of-life value will show profit or cost which can be achieved from the appropriate end-of-life option decided for each component. The end-of-life option, mass of the component, material type, and end-of-life cost are input for computing the end-of-life value. The end-of-life value can be used as the indicator to show whether a component adversely impacts the environment or not. A component which impacts the environment will require special handling and the deficit incurred by special handling is indicated by the negative sign of the end-of-life value.

The disassemblability evaluation will aid the designers in reducing disassembly difficultness, disassembly time, and disassembly cost required. The recyclability analysis will show that the design meets or does not meet the requirements legislated. Although the objective of the legislation is laudable and, theoretically all materials are recyclable, operating costs are still one of the primary concerns of manufacturers. Therefore, the economic aspects were involved in quantifying the recyclability. In order to determine that a component is suitable for recycling or not, suitability for recycling is used as the indicator. It is the ratio between the cost (in currency unit/kg) of a new material equivalent to the recycled material and the cost of disposal (on a landfill or through incineration) if the material is not recycled, versus the costs of disassembly, reconditioning, and logistics.

7 Conclusion

A very important contribution of this research is that the developed methodology integrates the end-of-life option determination and disassemblability evaluation in one framework. The end-of-life options determination and the disassemblability evaluation will show how economically efficient it is to disassemble an end-of-life vehicle and check the opportunity of a component to be recycled. Besides that, the disassemblability evaluation report provided by the methodology can be used by product designers to identify weaknesses of the design and do further improvement.

Due to broad scope of disassembly and recyclability analysis, the proposed methodology and software can be further improved as described below:

1. For determining the end-of-life option, the Multi-Criteria Decision Analysis can be integrated into the developed methodology to select the appropriate end-of-life option of the product's components because the selection of the end-of-life option is also subjected to the economic, environmental, and social factors. In this work, it is based on the material composition of the end-of-life components.
2. In order to estimate the disassembly time, the developed methodology only provides the disassemblability scoring system for manual disassembly operation.

In order to accommodate the disassembly operations which are not done manually, the database of the disassemblability scoring system can be enriched with database for estimating the disassembly duration of the automatic disassembly operation.

3. For a better cost and profit comparison, it will be more realistic if indirect costs are also considered in defining the disassembly cost. In the developed methodology, the disassembly cost is assumed equal to labor cost per unit of time.
4. Implementing this methodology to the computer program will make it a very useful tool for the product designers. It can provide assistance in making decisions at the early stage of the product design and development process in order to avoid the cost and time consumed through later redesign.

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