Sustainable product family design and a platform strategy

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SUSTAINABLE PRODUCT FAMILY DESIGN AND A PLATFORM STRATEGY

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Abstract

With awareness of environmental concerns growing at an ever-increasing rate, environmental regulations are becoming more stringent which is leading product designers to factor-in an extra feature into their designs: sustainability. Modular product design has been researched to consider product lifecycle including manufacturing, use, and end-of-life stages. As most modular product design has been developed for primarily manufacturing purposes, the design lacks the ability to configure and assess modules for the end-of-life stage. Since a product recovery strategy at the end-of-life stage has potential to meet the environmental regulations and earn economic and social benefits, the product recovery strategy must be considered for sustainable product design. This research proposes a sustainable product family design methodology (SPFDM) to incorporate sustainability performance into module-based product family design. Product design features including functionality and architecture have a major impact on the economic and environmental performances at the product recovery stage. By incorporating sustainable design at the product architecture design level, the proposed methodology extends and reinterprets the current product family design to enhance product recovery. In this research, new concepts of sustainable design methods are introduced to: 1) evaluate disassembly complexity and modularity of products from the viewpoint of the product recovery, 2) provide modular architecture to show how sustainable modular drivers affect the modular architecture to improve recyclability and reusability, 3) determine a sustainable platform for a product family by considering not only commonality, but also sustainability and risk of redesigning products, and 4) identify a sustainable product family to enhance economic and environmental performances by considering manufacturing and end-of-life (remanufacturing) stages simultaneously. To demonstrate and validate the effectiveness of the proposed SPFDM, case studies have been performed with product families of coffee makers and electric shavers. The main contribution of the SPFDM is to provide a foundation for modelling

the link between product design and sustainability performance that incorporates environmental, economic, and social aspects. Accordingly, the proposed product design methods can help determine how to evaluate which design is more sustainable than other design, and then apply the evaluated information into product family design. The SPFDM can be used to develop design strategies to manage and enhance product lifecycle to meet environmental regulations and customer requirements.

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List of Abbreviations

BOM:	Bill of Material
CI:	Component Complexity Index
CPA:	Change Propagation Analysis
CPI:	Change Propagation Index
DfD:	Design for Disassembly
DfE:	Design for Environment
DfS:	Design for Sustainability
DFPR:	Design for Product Retirement
DSM:	Design Structure Matrix
EI:	Environmental Impact
ELV:	End-of-Life Vehicles
EOL:	End-of-Life
EuP:	Energy Using Product
FC:	Functional Compatibility
FIS:	Fuzzy Inference System
GA:	Genetic Algorithm
GHG:	Green House Gas
GRA:	Grey Relational Analysis
IC:	Interface Compatibility
II:	Interface Complexity Index
ISO:	International Organization for Standardization
LCA:	Life Cycle Assessment
MADM:	Multi-Attribute Decision Making
MCL:	Markov Cluster Algorithm
MCS:	Modular Complexity Score
MDL:	Minimum Description Length

MFD: Modular Function Deployment

MI: Module Independence

MNL: Multinomial Choice Model

MS: Module Similarity

PC: Physical Compatibility

PDC: Product Disassembly Complexity

QFD: Quality Function Deployment

QL: Quality of Retrieved Module

SCCI: Single Component Complexity Index

SPFDM: Sustainable Product Family Design Methodology

WEEE: The Waste of Electrical and Electronic Equipment

wMCS: Weighted Modular Complexity Score

Chapter 1. Introduction to Sustainable Product Family Design

1.1 Background

Countries in the world have been suffering from environmental problems due to the impact of climate change [1-3]. With world population on the rise, the primary concern of governments and international organizations is how to sustain our depleting natural resources by lessening the damage to the environment. As the environmental problems are an extensive and complex problem, existing studies in various fields of engineering are researching about energy consumption, material/resource use, product recovery, and eco-design to solve and prevent the problem during product lifecycle [4, 5]. Governments and international agencies have designed not only domestic regulations but also international regulations encouraging designers and manufacturers to take stronger environmental stewardship [6]. Environmental regulations, such as the Waste of Electrical and Electronic Equipment (WEEE), Energy Using Product (EuP), and End-of-Life Vehicles (ELV), were introduced by concerning fabrication and disposal of products [7].

In product design, growing issues of environmental problems including global warming in the last decades led to emerging eco-design or design for environment. The eco-design is the combination of environmental performance and design, and has focused on how to measure the environmental impact of products based on life cycle assessment (LCA). On the other hand, a scope of a sustainable product contains not only the eco-design but also social and economic performances. Sustainable products are more environmentally friendly and profitable with enhancing social benefits during product lifecycle [8]. The goal of sustainable product design contains developing a design methodology to produce economic and social benefits, and less pollution and waste during the entire product lifecycle in early product design stage. There are three

considerations for significances of sustainability in the field of the product design. The first is that the sustainable product has to minimize landfill rates and environmental impacts. For example, as technologies are developed rapidly, consumers have opportunities to use high-end products, especially electronic products. Simultaneously, although a product is good enough to use, product lifespan becomes shorter because of a technology push strategy and/or a market pull strategy of a company [9]. As a result, high production volumes in a firm and frequent product replacements from consumers cause high raw material consumptions and landfills of the end of life (EOL) products, so that it has a negative effect on the environment [9]. Therefore, it is necessary for products to be sustainable. Secondly, the sustainable product should consider multiple improvements in environmental, economic, and social performances. This is because the concept of the sustainable product design requires a system-level thinking of senior level management, design managers, and designers to balance ‘triple-bottom line’: environmental, economic, and social needs. In particular, the sustainable product design will be developed in ‘closed-loop’ product lifecycle towards product recovery. Lastly, the sustainable product will compete with existing products. It means that the sustainable product should satisfy functionality of the product itself while meeting environmental, economic, and social performances.

In order to develop a sustainable product, there are two main areas that need focus [10]: 1) *innovation for the sustainable product* by redesigning and developing new sustainable products; and 2) *the end-of-life product management* which focuses on product recovery strategies like remanufacturing, recycling, reconditioning, reusing and disposing. The innovation stage can be more beneficial for eco-design to enhance environmental benefits than the end-of-life management stage as shown in Figure 1.1 [10]. This is because the innovation stage, which is called as early product design stage in the field of product design, has design freedom to consider not only the environmental benefits but also economic and social benefits. On the other hand, the end-of-life product management stage has limitations and restrictions to improve

environmental benefits dramatically because of the fixed product design information. Since the end-of-life recovery aims to recover the product from an obsolete condition to a serviceable condition, it has environmental benefits by conserving natural resources and has economic benefits by reducing an amount of raw materials and energy to produce new products [11, 12]. Accordingly, it helps avoid production of new materials or parts/modules. To support both stages simultaneously in the product design, modular product family design should be considered to apply sustainable aspects in early product design stage.

Figure 1.1 Four step approach to eco-design (adopted from [10])

1.2 Motivation

In an era of mass customization, product variety plays important roles in the satisfaction of customers in the markets. Companies have put a lot of their efforts to develop new products for the mass customization by reducing production cost and lead-time without sacrificing performance and quality [13]. To fulfill customer requirements in different market segments, the companies have applied different modules to create product family design in order to improve responsiveness and flexibility from customers' needs and share assets such as components/modules, processes, expert knowledge of products. A

module is defined as a physical or conceptual chunk of components [14]. The concept of modularity is to separate a system or product into independent components or modules. The modularity has one-to-one mapping between functional and physical structures of a product while minimizing unintended interface between modules [14]. Accordingly, the principle of the modularity is to maximize internal coupling within modules and minimize external coupling between the modules [15-17].

Research trends seek to apply and extend the modular design into the design for sustainability over the product lifecycle including manufacturing (assembly), use, and end-of-life stages (reuse, recycling, and disposal) [18]. Modular product design can be one of the most important considerations to sustain the used products, and motivate customers to use the products longer by substituting the latest modules for out of date modules [19]. Therefore, the modular product design would be a baseline for designing a sustainable product in terms of product architecture. Successfully designed modules can be easily added, substituted, and/or removed from a final product [20].

Recently, as a technology has been developed well, the degree of modularity of a product is getting higher. It means that modules are highly independent and have standard interfaces to interact with the modules. For example, Project Ara of Google¹ aims to develop an open hardware platform by creating a highly modular smartphone. BLOCKS² is the world first smart watch with the strap that consists of highly independent modules with functions. LG G5 mobile phone³ was released with several modules to add more functions into LG G5 mobile itself. As each module in these products has functions, users can customize these products by adding new features or upgrading their existing ones to expand the functionality. It would give users to actively involve modular product design for customization.

¹ <http://www.projectara.com/>

² <http://www.chooseblocks.com/#homepage>

³ <https://www.lgmobile.co.kr/lgmobile/front/main/mainList.dev>

Figure 1.2 Example of modular products: Project Ara of Google, BLOCKS, and LG G5 (clockwise)

However, a few researchers proposed assumptions that the modular architecture of a product influences sustainable design with considering manufacturing cost, difficulty of disassembly, and recovery process of retired products at the EOL stage. Also, the sustainable benefits of modular product architecture and product family design over the product lifecycle have not been researched completely. Therefore, a novel method is needed to indicate sustainability of the modular product architecture and determine new concept of sustainable product family design based on a platform strategy. For the sustainable product family, the current concept of platform design should be extended with consideration of environment and product recovery in early product design stage. In this dissertation, it has more focused on product recovery strategies at the end-of-life stage with environmental impact over the product lifecycle.

1.2.1 Modular Product Design and Product Lifecycle

Sustainable product design considers not only manufacturing process but also whole product lifecycle. The goal of sustainable design involves managing product lifecycle to reduce pollutions. The product lifecycle as shown in Figure 1.3 starts with its design and development. After deciding product specifications, raw materials are extracted and processed for part manufacturing. Then, the parts are assembled into final products through sub-assemblies (module). The final products are distributed via companies' supply chain to customers. The customers purchase and use the products. When the products reach to their end-of-life, the products are discarded [21]. All product lifecycle stages from raw material to end-of-life stages exacerbate the environment by depleting natural resources, and energy; and producing emission and waste. It causes climate change. Therefore, the entire product lifecycle must be enhanced to generate less environmental impact.

Figure 1.3 Product lifecycle and various end-of-life recovery options (modified from Kwak [21])

To sustain products, the EOL recovery is a promising solution to the challenges of achieving sustainable product design and sustainable business. The product recovery is a process of restoring the inherent value of retired products when the products no longer satisfy customers' needs [22]. Main contribution of the product recovery is to eliminate

the amount of waste disposal and the usage of natural resources, and increase profits by recovering obsolete parts to serviceable parts as shown in Figure 1.3.

There are five types of EOL recovery options: material recycling, refurbishment, remanufacturing, cannibalization and reuse [23-25]. The material recycling is the popular strategy of the product recovery. The material contents of the used and non-functioning products like steel, glass, plastic, and aluminum, are recycled to make new parts. The refurbishment and remanufacturing are the processes of restoring components to functional and satisfactory state as a like-new condition. The refurbishment aims to keep original specification, while the remanufacturing is to maintain the original specification and upgrade the specification for better performance [21]. Refurbished and remanufactured components can be reused in the product assembly stage. However, the cannibalization aims to resale the recovered components in the second-hand market. The reuse is an optimal product recovery option because EOL products are used by the second customers as originally designed without any value adding treatments. It demands minimum effort and resources to recover a serviceable product.

In order to improve sustainability, especially EOL recovery, previous studies for modular design stand on a principal hypothesis that product architecture plays a pivotal role in identifying product recovery characteristics (e.g. disassembly, assembly, recycling, and other post-life characteristics) because of the advantages of modular product design as follows:

- Ease of assembly and disassembly because of weak interactions between modules [26]
- Product complexity reduction by grouping components into a module [27]
- Operation (manufacturing) costs reduction because of a reduction of the number of physical components [28]
- A way to shorten product development time [27]

The modular products have been analyzed to continuously improve modular architectures from the viewpoint of product lifecycle, such as recycling, post-life, and service intent [29]. It implies that the best modular architecture has highly independent modules and satisfies various viewpoints from lifecycle. Ishii, et al. [30] evaluated modular design from various stages of product lifecycle and measured disassembly and reprocessing costs. According to designers' intent and expert knowledge, the modules were determined to facilitate disassembly at the end-of-life stage. Kwak, et al. [7] identified eco-modular architecture to improve ease of disassembly and maximize the end-of-life value. These studies generated modules that consist of components with similar materials and lifespans to encourage the product recovery process. In reply to this situation, a more reliable modularity measure is needed to reflect product lifecycle.

1.2.2 Product Family Design and Sustainability

A product family is defined as a set of related products to satisfy various market segments based on product platform strategy [31]. A product family has two different types for satisfying various market niches. The first is a scale-based product family that shares scaled or stretched design variables to cover various markets [20]. The second is a module-based product family which one or more functional module can be added, substituted, and/or removed from platform to improve a variety of product [20]. In order to support these product family types, three platform leveraging strategies have been studied: horizontal leveraging, vertical leveraging, and beachhead leveraging which is a combination of both [32]. These product families aim to improve economies of scale and manufacturing efficiencies. However, since product design coupled with sustainability is critical, it is necessary to cover lifecycle needs related to sustainability. Umeda, et al. [33] insisted that a new concept of modular product architecture for product family design is needed to minimize environmental loads and costs during whole product life cycle. The new modular product architecture design aims to group

components with similar attributes related product lifecycle, such as product lifespan, constituent materials, and value lifetime. For example, grouping components with similar design characteristics and product recovery processes into modules can facilitate the processes from product lifecycle [33]. If components with different materials and lifespans are mixed in a module when disassembling a product, disassembly operators make more efforts to disassemble the module to material level [34]. When practicing the new modular architecture, it can facilitate product lifecycle processes efficiently according to objectives of the lifecycle stages. After that, the new modular architecture should be assessed to know how the modular architecture is developed by reflecting designer's intent related to the sustainability. Newcomb, et al. [29] insisted that modular product architecture plays a pivotal role in identifying lifecycle characteristics and has an effect on its initial costs, ease of service, and efforts required to the end-of-life stage. Then, the modular product architecture with respect to lifecycle concerns was introduced to allow one-to-one correspondences between physical structure and lifecycle concerned structure. In order to measure the modularity from lifecycle viewpoints, a modularity evaluation tool was developed to meet function, service, and post-life goals. Since the tool focused on correspondence between two modular architectures and the degree of cluster independence, it is difficult to assess single product architecture and lifecycle characteristics of each module. Yang, et al. [35] emphasized the importance of a platform strategy because all product family cannot be developed one by one. Since a platform is emergent attributes of the product family design that can lead to mass production, the platform strategy has high possibility to affect environmental performance by sharing and reusing the platform. In other words, any modification of the product family for sustainability will affect the platform strategy, and then it will affect other products in a product family. Therefore, a new concept of modularity assessment tool is needed to evaluate whether or not the modularity of a product reflects designers' intent for lifecycle characteristics. Also, a new concept of the

sustainable platform should be researched to concern environmental performance of sustainable product family design.

To sum up, although modular product design has potential to improve sustainability with the product lifecycle, the modular product design has been mainly focused on benefits of a manufacturing stage rather than other stages in the product lifecycle. Accordingly, it is needed to facilitate sustainable benefits of modular product design and product family design with the product lifecycle.

1.3 Research Objective

The principal objective of this dissertation is to develop a sustainable product family design methodology (SPFDM) by extending modular product architecture with considering sustainability performance. A new concept of a platform, called as a sustainable platform, is identified to extend sustainable product design in a single product level to a product family level under a dynamic and uncertain market environment. Improving product design for sustainability can be achieved by planning how the modular product will be redesigned for enhancing end-of-life recovery, and what environmental and economic implications the modular design decision will be resulted in at the end-of-life stage. However, current product design has been mostly emphasized manufacturing efficiency. Namely, connections between the product design and sustainability have been not clear, so that it hinders the product design towards sustainable products. The methodology presented in the dissertation will help build clear links between product design and sustainability factors. Before designing sustainable product, products should be evaluated to know design condition from the viewpoint of sustainability as shown in Figure 1.4.

Figure 1.4 Produce design evaluation through Design for Sustainability

To achieve the main objective, the following sub-objectives are investigated:

- Develop the assessment method of product complexity to understand disassembly difficulties for product recovery according to component design, interface design, and the number of components/interfaces
- Develop an eco-modular architecture to enhance product recovery processes like recyclability and reusability by facilitating sorting process, and grouping components with similar design specifications into modules
- Develop a new concept of a modularity assessment method from the viewpoint of the product recovery
- Assess and compare degree of sustainability of products by considering environmental, economic, and social performances based on a multi-attribute decision making approach
- Predict unexpected design changes of components/modules and change propagation paths from the design changes based on product dependency analysis and Bayesian network
- Identify a sustainable platform to improve current platform identification methods by integrating sustainability values, dependencies between components and its effects in terms of product architecture

- Identify a sustainable product family with an EOL platform to maximize profits and minimize environmental impact from manufacturing and remanufacturing

1.4 Significance of the Research

Main contribution of this research is that it provides the SPFDM by integrating these perspectives on sustainable design, such as modular product design, eco-design including environmental impact, and product recovery strategy. Concepts from product family design based on a platform strategy are extended to the sustainable product family design to concern environmental, economic, and social performances.

Another contribution is to develop assessment methods. As there is a great deal of study conducted on design for manufacturing, most of interest in previous studies has been focused on assembly processes, such as assembly time and cost. However, for the success of sustainable product design, assessment methods from the viewpoint of the end-of-life recovery and product lifecycle are needed to measure the difficulty of disassembly process, the degree of modularity, and the degree of sustainability. These assessment methods result in quantification of the current status of product design and help plan how to improve sustainability. Therefore, this dissertation introduces and applies these assessment methods to product design.

Finally, modular product architecture design is a primary focus in this dissertation because it is most popular and effective form of product architecture for production, maintenance, upgrade, and product recovery strategies. Based on the modular product architecture, new concepts of product architecture, platform, and product family design are developed to facilitate end-of-life recovery operations and become more sustainable.

1.5 Research Scope

This research will focus on an investigation of modular product architecture with considering product lifecycle for developing a sustainable product family as shown in Figure 1.3. In order to describe the sustainable product family, this methodology is approached from the viewpoint of product architecture design. Therefore, this study aims to reinterpret current modular product architecture that has mostly focused on manufacturing, adding product lifecycle, especially, product recovery strategy. This study helps designers redesign current products to sustainable products at the early product design stage.

1.6 Overview of the Dissertation

This dissertation is organized into 8 chapters and the overview of the chapters is represented in Figure 1.5.

Chapter 1 introduces the concept of the sustainable product and provides the motivation to develop modular product design for sustainability, especially, end-of-life performance. Additionally, the research focus with goal and scope is presented. Chapter 2 elaborates literature reviews of the related state-of-the-art research. The existing design methods are reviewed along with design for environment, product recovery strategy, product redesign, and product family design. The framework of the proposed sustainable product family design methodology is illustrated in Chapter 3. Chapter 4 introduces an assessment method of product disassembly complexity to understand product architecture for product recovery in terms of components and interfaces. Chapter 5 demonstrates determining eco-modular product architecture based on sustainable modular drivers, and assessing modularity for the product recovery to evaluate and select the eco-modular architecture. Chapter 6 is to identify a sustainable product platform based on not only commonality but also sustainability values and risk

in redesigning products. Chapter 7 presents identification of sustainable product family configuration based on the eco-modular architecture and EOL platform. A multi-objective optimization model is developed to configure new products and remanufactured products for sustaining products in the product family by reusing end-of-life modules.

In each chapter, a specific design problem is identified; the steps of the proposed method are performed and evaluated based on case studies with coffee makers and electric shavers, and the results are discussed. In terms of the case studies, chapter 4 uses coffee makers and electric shavers; chapters 5 and 6 uses coffee makers; and chapter 7 uses electric shavers which have more diverse modules than the coffee makers for case study. Chapter 8 is the final chapter and contains a summary of this dissertation. Also, contributions and limitations of current work are discussed, and direction of future works is suggested.

Figure 1.5 Overview of this dissertation

Chapter 2. Literature Review

Given research focus identified in Chapter 1, literature reviews of relevant studies of product family design for sustainability are presented in this chapter. Design for Sustainability (DfS) is systematic consideration of design performance to fulfill environmental, economic, and social objectives during product lifecycle. DfS can break down into many methods to support specific manufacturing and/or recovery processes by means of design improvement. As shown in Figure 2.1, the relevant studies can be clustered into four groups: design for environment, product recovery strategy, product redesign, and product family design.

Figure 2.1 Relevant literature discussed for the sustainable product family design

2.1 Design for Environment

2.1.1 Eco-product Design

Every process in the product lifecycle has generated environmental impact. Since product design is able to affect product lifecycle, design for environment (DfE) has been researched. The DfE is a practical design method to systemically consider the environment, health, and safety over the product lifecycle [36]. The DfE aims to minimize direct and indirect environmental impacts over the product lifecycle. The DfE has been similarly called as follows [14]:

- Sustainable product design
- Green design
- Eco-design
- Environmental design/Design for environment
- Lifecycle design/Design for lifecycle

The eco-design considered environmental impact during product design and development processes at early product design stage. Most of the previous works used lifecycle assessment (LCA) for assessing the environmental impact and then select eco-design. The LCA has been recommended by the 14040 series in International Organization for Standardization (ISO) [37]. LCA is a fairly detailed and quantitative design tool [1]. LCA consists of four development steps in reference [37]. First, scopes and boundaries are defined to develop well-designed lifecycle stages because LCA can depict the whole product development process, material flow, or service. The system boundaries are decided to limit data collection ranges in this step and affect the sustainable impact to the environmental index and the traceability about pollution. If the system boundary ranges from whole lifecycle stages, an engineer can audit the variance of environmental factors according to production and trace the reason why pollution is increasing. Also, functional specification is determined in this step. Material and energy

are the inputs of LCA, while the output is residues with various states like gas, water or solid [38]. Second step is to develop lifecycle inventory including information on inputs and outputs related to the environment. Third step is to assess environmental impacts of the data in the lifecycle inventory. The last step is to analyze the result from step 3. Through these steps, LCA can assess the environmental impact of product lifecycle and propose which processes and/or stages will be improved.

Lu, et al. [38] introduced a systematic lifecycle design method to develop an environmentally friendly product. The simplified LCA was used to assess each of the materials related to the physical structure of the product and process in the lifecycle; it determined whether or not the product was sustainable based on the rating values from expert knowledge. Jeswiet and Hauschild [39] described that environmental problems must be identified at the early product design to reduce negative impacts on the environment and design the environmentally friendly product. Lofthouse [40] described a web-based eco-design framework for designers who need to consider eco-design strategies within their design work. Deutz, et al. [41] derived the importance of an effective regulatory strategy to implement eco-design in companies from interviews and a survey. The characteristics of these eco-design tools are either too qualitative or too quantitative. So, Devanathan, et al. [42] introduced a semi-quantitative method for the early product design stage. The method focused on the QFD including the environmental impact. This environmental indicator was considered as carbon footprint from LCA and then its impact was assigned according to distributed contribution percentages in function impact matrix. Mayyas, et al. [43] presented four categories about automotive LCA, design for X, product end of life, and material selection to assess environmental impacts in sustainability in terms of automobile industries.

2.1.2 Eco-product Design Tools

As the concept of sustainability is still developing, various definitions of the sustainability have derived from the basic definition on Brundtland Commission report [44]. To consider the sustainability, outputs and/or byproducts during product lifecycle would be assessed to indicate the degree of the sustainability. There are various eco-design methods to evaluate whether a product is sustainable or not.

The methods are classified into four categories such as guidelines/standards (e.g., BS 8887-1, UNE 150301, ISO 14000 series, Greenhouse gas protocol, WEEE regulation), checklists (e.g., Smart ecoDesignTM checklists), comparative tools (e.g., Lifecycle development strategy (LiDS) wheel, Eco-compass, Eco-design decision support system), and analytic methods (e.g., Environmental effect analysis, Environmental impact assessment, Life cycle assessment, Energy and toxicity matrix, Eco indicator 99, ReCiPe) [45-47]. Devanathan et al. [42] and Ramani et al. [1] classified various 30 eco-design tools to three categories as shown in Table 2.1: (1) Lifecycle assessment (LCA) based tool, (2) Checklist based tool, and (3) Quality function deployment (QFD) based tool. Firstly, LCA based tool is to identify environmental impacts as holistic monitoring of product lifecycle. It is a fairly detailed and quantitative design tool [1]. Since LCA assesses the consequence of products based on massive data from product life cycle, it is the most objective tool than others and proposes which processes and/or stages will be improved. Detailed information on a trend of the LCA application in sustainable product development with the promising research directions for LCA studies are well elaborated by Chang, et al. [48]. Another category for the eco design is the checklist based tool. The tool is the most common and easiest approach to assessing environmental impact during whole product life cycle. This tool is flexible, so that it can be applied to early product design. When analyzing the checklist, designers should have comprehensive understanding and knowledge of different life cycle stages to analyze and decide the balanced outputs from the checklist.

Lastly, QFD is a traditional way to convert the voice of the customer to technical specification. For considering sustainability in early product design stage, environmental factors, like carbon footprint, can consider as customer needs [42]. Since QFD has been used to generate concepts and functions, QFD including environmental requirements can be the most suitable in early product design stage.

On the other hand, these tools have drawbacks as shown in Table 2.1. As the LCA-based tool would assess environmental impact based on detailed and massive data of products that are producing in factories, this tool is difficult to properly support the environmental impact for new product design [42]. Also, it is a costly and time-consuming approach and does not consider economic and social performances. In case of the checklist based and QFD based tools, it is subjective to identify relationship between environmental factors and engineering specifications. The checklist based tool can be designed to contain environmental, economic, and social performances, but it is so subjective that the tool is hard to compare the result of assessment in different life cycle stages and in different categories of sustainability [1].

Table 2.1 Category of eco-design tool (summarized in [1, 42])

	LCA based tool	Checklist based tool	QFD based tool
Type	Quantitative tool	Qualitative tool	Qualitative tool
Aim	To measure environmental impact during holistic product life	To measure environmental impact during holistic product life	To convert environmental needs to engineering specification
Advantages	A holistic approach, The most objective	The easiest approach, Flexible	Yields an engineering specification from the environmental needs
Disadvantages	Not design oriented, Very costly, Very time consuming	Subjective	Totally subjective
Application in early design stage	No	Yes	Yes
Related literature	ISO 14040 [49]; Lu et al. [38]; Devanathan et al. [42]; Inoue et al. [50]	Howarth and Hadfield [2]; Mayyas et al. [43]	Devanathan et al. [42]; Sakao [51]

2.2 Product Recovery Strategy

2.2.1 Disassembly Planning for Recovery Strategy

Product recovery at the EOL stage is a promising solution to the challenges of achieving sustainable product design and sustainable business. The product recovery is a process of restoring the inherent value of retired products when the products no longer satisfy customers' needs [22]. Reusable components and modules, and recyclable materials are retrieved from the retired products. The main contribution of the product recovery is to minimize the amount of waste disposal and the usage of natural resources by recovering obsolete parts to serviceable parts. Recovery options include recycling and reuse; additionally, reconditioning, refurbishment, and remanufacturing options are utilized to retrieve products or modules for reuse [23].

In order to consider the product recovery in early product design stage, design for disassembly (DfD) was researched to easily and effectively take products apart for reuse and/or recycle in the EOL stage [52]. DfD has mainly focused on identifying the optimal disassembly sequence of a product by minimizing disassembly cost and time. Lambert [53] described three types of disassembly representation: tree representation, state representation, and AND/OR graph representation. The representations contain nodes that are states of disassembly and arcs which describe disassembly operation based on precedence relationship. Based on the graph representation, Lambert [54] introduced a method for solving a disassembly sequence generation problem and a disassembly sequence clustering problem by using linear programming. Behdad, et al. [55] determined an optimal disassembly sequence planning by applying stochastic modeling and immersive computing technology. The stochastic modeling resulted in minimizing disassembly time and damage to components during the operations, while the immersive computing technology was applied to identify solutions based on human intuition. GÜngÖr and Gupta [56] developed an approach to generate disassembly sequence plans for product recovery by using hierarchical tree representation and a branch and bound

algorithm. They resulted in the optimal disassembly sequence with the lowest cost. Smith and Chen [57] presented a rule-based recursive method for finding the lowest cost of selective disassembly sequence planning. Sung and Jeong [58] developed a heuristic algorithm for disassembly planning and mathematical modeling to find minimum disassembly cost.

As aforementioned, the studies for the disassembly sequence planning have emphasized on applying an optimization method to find an optimal disassembly sequence for minimizing disassembly cost and time. The previous studies mainly identified optimal sequence based on components' relationships with precedence matrix. To consider more specific attributes for disassembly, Tseng, et al. [59] proposed a method for disassembly sequence generation with cost functions related to operation, stability, accessibility, tool setup, and weight effect costs for disassembly, to reflect design for disassembly. Rickli and Camelio [60] optimized partial disassembly sequence by considering disassembly operation costs, recovery reprocessing costs, revenues, and environmental impact. In these studies, attributes related to the difficulty of disassembly were rarely considered, and the disassembly sequences were decided based on disassembly cost. Therefore, design for disassembly is necessary for profitable and environmental-friendly product recovery. Efficient disassembly helps retrieve valuable and reusable parts or modules, and remove hazardous or toxic materials. The design guidelines for the product recovery in Table 2.2 are summarized based on literature [7, 30, 34, 61].

Table 2.2 Design guidelines for product recovery

Product architecture guidelines	Interface related guidelines	Material selection guideline
<ul style="list-style-type: none"> - Minimize the number of parts - Create multifunctional parts - Make designs as modular as possible, with separation of functions (for service, upgrade, recycling) - Design a reusable platform and reusable modules - Locate unrecyclable parts in one subsystem that can be quickly removed (selective disassembly) - Design parts for stability during disassembly 	<ul style="list-style-type: none"> - Minimize the number of fasteners - Minimize the number of fastener removal tools needed - Fasteners should be easy to remove - Fastening points should be easy to access - Try to use fasteners of material compatible with the parts connected - Make them easy to separate if two parts cannot be compatible (for recycle) 	<ul style="list-style-type: none"> - Avoid regulated and restricted materials - Minimize the number of different types of material in a module - For attached parts, standardize on the same or a compatible material - Use less different types of materials in a module - Use recycled materials - Avoid composite materials that are not amendable to recycling

2.2.2 Modular Product Design

2.2.2.1 Modularization

For successful product recovery, modular product design has been researched as one of the solutions to improve disassemblability, and manage the efficiency and difficulty of the disassembly. The definition of product architecture is “the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact [62].” The product architecture of complex mechanical and electro-mechanical products embedded information on the amount of components and interfaces, its functionality, and schemes for assembly and disassembly [26]. The most important characteristic of the product architecture is modularity by which a physical chunk meets one functional element of a product [62]. The modularity is developed for the purpose of manufacturing production [63]. The main principle of the module identification is to improve internal coupling within modules while minimizing external coupling between modules [64]. The modular architecture has been developed to improve device configurability, maintainability, serviceability [34], and disassemblability for end of product lifecycle [29].

In order to identify the modules, product architecture was largely represented by matrix and graph based representations. Matrix-based representation makes up rows,

columns and matrix elements. The rows and columns are developed by component lists, and the matrix elements represent functional or physical relationships between the components. The matrix elements have a binary value to show the connectivity between components or weighted value to show the strength of connectivity. As for the product information to be used for modularization, physical structure information and functional information were mainly considered. Firstly, physical relationships are fundamentally used to identify modules. The design structure matrix (DSM) is a popular method to represent the physical relationships between components. Yu, et al. [65] considered the physical relationships using the DSM method and applied minimum description length (MDL)-based clustering method with a genetic algorithm (GA) to identify modules. The feature of the clustering method is to allow bus modules and overlapping modules. Yan, et al. [66] utilized the DSM to establish the correlation between the components based on the strength of interaction and then identified modules with the kernel-based fuzzy c-means algorithm. Secondly, with regard to functional information, Helmer, et al. [67] used information values about types of interactions, such as structural, spatial, signal, material, and energy, from the research of Pimmler and Eppinger [68] and Sosa, et al. [69]. Huang and Kusiak [70] interpreted three types of modularity, namely, component swapping, component sharing and bus modularity, and determined modules based on the decomposition approach and three axioms related to the three types of modularity. To identify the three modules, physical interactions and suitability values were considered in the DSM. The minimum description length (MDL)-based DSM clustering was utilized to cluster modules based on the types of functional interactions. Asikoglu and Simpson [71] measured the weighted modular complexity score (wMCS) according to different types of interfaces. Then, Jung, et al. [72] used the wMCS and the GA to improve the modularity of products. Heuristic methods are also applied to modularize functional structures based on shared and unique functions [73-75]. By utilizing the heuristic method, a group that shares similar functions and flows should be clustered in a single module, and components with unique functions can be grouped in a module.

Erixon [76] introduced the modular function deployment (MFD) that heuristically determines modules by maximizing similarity technical solutions in terms of module drivers.

Aforementioned methods developed modules based on either the physical relationship or the functional relationship. To overcome this issue, Borjesson and Hölttä-Otto [15] suggested a new modularization algorithm to consider both the DSM for the physical relationships and the MFD for functions. Meng, et al. [77] proposed a multi-objective combinatorial optimization problem for module identification by using the GA. To consider module configurability, these kinds of information were analyzed and used as follows: the simultaneous use of module alterability and module manufacturing efficiency; and both physical and functional information, such as functional relationships and structural relationships.

2.2.2.2 Modularity Assessment

After identifying various module candidates by considering various information, the modularity assessment of the module candidates is necessary to evaluate whether the modules are well-clustered to meet designers' intent or not. Fixson [26] introduced product architecture assessment with a function-component allocation scheme to distinguish modular or integral architectures. Chiriac, et al. [19] analyzed modular product architecture to determine the degree of modularity and the level of system granularity. Newcomb, et al. [29] developed similarity metrics to assess modularity for the EOL stage by comparing the correspondence of the inner module's connection between more than two product architectures for the product lifecycle. Moreover, the interface design related to compatibility and interchangeability was significantly considered when the module was defined. Well-designed interfaces can minimize complexity and uncertainty in disassembly operation. Pimmler and Eppinger [68] measured the degree of generic interaction by using categories of energy, spatial, information, and materials. Fixson [26] additionally analyzed the reversibility of

interfaces for product changes during product lifecycle, such as upgrades, adaptation, wear, or reuse, together with interface standardization. Dobberfuhl and Lange [78] proposed a modular complexity score (MCS) to identify the degree of modules' complexity. Asikoglu and Simpson [71] introduced wMCS based on the MCS. The wMCS includes six different types of interface and its weight value. Jung and Simpson [79] developed two modularity indices to measure the proximity of components to the diagonal of the DSM and to measure modularity independency.

2.2.2.3 Modular Product Design for Sustainability

Few studies dealt with modular product architecture and/or product family design for sustainability. Kwak, et al. [7] introduced a new concept of eco-architecture to allocate modules with the EOL strategy from the viewpoint of product retirement. Linear programming was used to identify eco-architecture that consists of eco-modules and its EOL strategy based on disassembly cost and an economic value. Behdad, et al. [80] extended the work of Kwak, et al. [7] to consider sharing disassembly operations between products with similar product architecture. Modular architectures were assumed and represented by a transition matrix based on a disassembly order. Ishii, et al. [30] introduced a module based design method for product retirement stage, and then evaluated the module based design based on quantitative retirement cost analysis and qualitative guidelines. The major factors of the evaluation method were material compatibility and system disassembly cost. Although these methods were built based on the modular architecture, module identification was assumed. Tseng, et al. [81] clustered modules based on liaison intensity values that measured assembled connections between components. The grouping genetic algorithm was applied to maximize the liaison intensity within the modules and to minimize the liaison intensity between the modules, as carried out in the conventional modularization method.

2.3 Redesign Method and Change Propagation Analysis

Product redesign is usually conducted to recover and refine functions and physical defects of products [82]. To identify potential and current customer needs, Shieh, et al. [82] introduced a customer requirement solicitation approach to support optimized product conceptualizations and design alternatives for the product redesign. Picture sorting was applied to elicit customer requirements, and then the multi-cultural customer requirement from the picture sorting was evaluated by ART2 neural network. Thevenot and Simpson [83] proposed a framework for product family redesign by using five different commonality indices. Each commonality index was classified according to strategies: total constant commonality index (TCCI) and degree of commonality index (DCI) for determining the degree of good design in the product family; percent commonality index (%C) for showing the component with lack of commonality and the reason; product line commonality index (PCI) and component part commonality ($CI^{(C)}$) for robust design. Devanathan, et al. [42] introduced a semi-quantitative product redesign method for the early product design stage which is developed based on function impact matrix and carbon footprint as an environmental indicator. Modular product design was employed to improve sustainability. The new modules for sustainability are reorganized by considering reusability and recyclability [35], modular driver for the end of life product [66], and lifecycle cost model [84]. The modules' compositions from conventional methods were compared to new modules.

During product redesign stage, although designers know that new components are added or design of current components is changed, it would be hard to apply the design change because of complex interconnections between components in product structure. As products become more complex with developing micro manufacturing, the product design for disassembly, recycling, and remanufacturing is getting more critical [39]. Accordingly, even when a design change to a component occurs, the design change propagates to other systems irregularly. The change propagation is defined as situation

that a design change to one component of an existing complex system results in multiple changes to the entire system [85, 86]. In this respect, Change Propagation Analysis (CPA), including Design Structure Matrix (DSM), change network, and Change Propagation Index (CPI), is applied to predict further effects on the change propagation while designing a complex product [85]. The study about the change propagation derives from design change and prediction under complexity, engineering design, and product development [86].

As a product has complex configuration, a design change causes other design changes that include the expected and unexpected changes. Figure 2.2 shows the source of changes in detail during whole product design process and proposes two different types of engineering changes [85]:

- Emergent change: by the intended and/or unintended occurrence of a problem during whole design process and product life cycle period
- Initiated change: by the requirement of customers or stakeholders

In the conceptual design stages between call for tender and contract, the initiated changes are determined to fulfill customer needs. Then, emergent changes are mainly considered to enhance the product quality in the period between contract and delivery. The feedback from customers while using the product can be acquired to maintain and improve the products in the stage after delivery. The vertical distance from horizontal axis means the impact of change proportionally.

Figure 2.2 The source of change during product design process (adopted from [85])

To understand design changes, the change propagation analysis was mainly visualized by DSM and graph theory [87]. Firstly, DSM was used as a method to show interconnection among components. The DSM was introduced to design a system structure based on interrelationship between elements in the same domain by Steward [87]. Clarkson, et al. [88] proposed the direct risk DSM that was the result of multiplication between the direct likelihood and the direct impact to determine the risky area according to design changes. Giffin, et al. [86] used a structural DSM with change propagation frequency in a software domain. The proposed approach divided the DSM area into three zones: predicted area, non-occurrence area, and unpredicted area. Secondly, graph theory was applied to illustrate a change network and investigate data set and change patterns [86]. A change propagation tree was proposed to understand the hierarchy between direct and indirect changes with the likelihood of changes and impact values [88]. Eckert, et al. [85] introduced four different types of components according to change propagation behavior: “*Multiplier, which generates more changes than they absorb; Absorber, which absorbs more change than they cause; Carrier, which absorbs*

a similar number of changes to those that they cause themselves; Constant, which is a unaffected component by change”.

The change propagation behavior can be classified by Change Propagation Index (CPI). Suh, et al. [89] proposed CPI with a binary matrix to measure physical change propagation. Giffin, et al. [86] developed the modified CPI to illustrate ambiguous areas in detail and then mapped these areas on the CPI spectrum ranging from +1 to -1. The change propagation is used to analyze individual components and decide which components should be changed while redesigning a product or recovering end-of-life product.

The CPI was utilized to classify the physical behavior of change in complex system [89]. The types of behaviors are defined as *multiplier*, *absorber*, *carrier*, and *constant* by CPI [85]. The Equation (2.1) is modified CPI equation by Giffin, et al. [86].

$$CPI_i = \frac{\sum_{j=1}^n \Delta E_{ji} - \sum_{k=1}^n \Delta E_{ki}}{\sum_{j=1}^n \Delta E_{ji} + \sum_{k=1}^n \Delta E_{ki}} = \frac{\Delta E_{out,i} - \Delta E_{in,i}}{\Delta E_{out,i} + \Delta E_{in,i}} \quad (2.1)$$

Where, n is the number of components. ΔE_{ji} is a binary number which represents whether i th component is affected by the change of j th components or not [89]. The numerator of the equation is the same as the CPI equation by Suh, et al. [89]. By dividing the numerator by total change input and output at an element, the result ranges from -1 to +1. CPI equal to 1 is perfect absorbers that do not generate any change but absorb changes, while the CPI value of +1 means perfect multipliers, which do generate changes without receiving change. The value similar to zero or equal to zero indicates carriers [86]. The degree of change behaviors could be analyzed: strong absorbers ranged from -1 to -0.3; weak absorbers ranged from -0.3 to -0.1; carriers ranged from -

0.1 to 0.1; weak multipliers ranged from 0.1 to 0.3; strong multipliers ranged from 0.3 to 1 [86].

2.4 A Sustainable Product Family Design Method

2.4.1 A Product Family and Platform Design Methods

In the competitive global market, many industries changed paradigm from mass production to mass customization according to increment of customer needs [20, 90]. In order to achieve mass customization, there are two main considerations: a high variety of products to fulfill different requirements of customers and the economies of scale without sacrificing performance and quality [13]. Accordingly, many companies and research fields are relying on product family and platform design to provide various products with intended performance while minimizing manufacturing cost [20]. The product platform provides opportunities to develop various products efficiently by capturing and utilizing commonality in order to anchor design features for future products to a common product line.

The product platform is common components within a given product family. As the platform must satisfy the functional or physical requirements of all products in a family, they would be more robust to changes under uncertainty. Simpson, et al. [31] introduced a product platform concept exploration method (PPCEM) to design a scalable product platform efficiently by determining trade-offs between commonality and performance loss. Chowdhury, et al. [91] introduced a comprehensive product platform planning (CP³) framework to develop a scale based product family based on a platform by maximizing performance and minimizing the cost. Chowdhury, et al. [92] modified commonality matrix and constraints of the scale based product family and then applied the commonality matrix and the constraints to a modular product family. de Weck, et al. [93] utilized two level optimization models: product platform model and product variant model. It aims to identify the optimum number of platforms to maximize

profits for a product family. Gonzalez-Zugasti and Otto [94] provided a method for designing a product family with modular platforms based on trade-off between performance and cost as well as between commonality and variety by using genetic algorithm. Moon, et al. [90] proposed a multi-objective particle swarm optimization approach to determine design variables of the optimal platform design based on the trade-off between commonality and product performance. Fujita and Yoshida [95] applied product variety optimization to optimizing both module attributes and its combinations at the same time with genetic algorithm and branch-and-bound technique. Martin and Ishii [96] proposed the generational variety index (GVI) to identify a product platform architecture for reducing redesign cost and efforts, which is robust components/modules under product redesign condition. Moon, et al. [97] introduced a platform and module identification method by using data mining techniques. Simpson, et al. [98] had integrated the market segmentation grid, DSMs, GVI, commonality index, and multi objective optimization to identify common components, unique components, and optimal parameter setting. Product platform candidates were identified by GVI value. Then, the platform candidates were verified by PFPF values and multi objective optimization for detailed trade studies. As a result, the platform candidates would have low GVI and PFPF. The low GVI means that the components are robust under product family redesign condition, and the low PFPF value represents maximizing commonality among the different parameter settings. Khajavirad, et al. [99] proposed decomposed multi-objective genetic algorithm (MOGA) to jointly identify optimal platform selection, platform design, and variant design. The product family optimization problem was divided into two level genetic algorithm: an upper level for platform configuration and each lower level for individual variant. Rai and Allada [100] proposed a two-step methodology to increase the level of platforming of a product family under multi objective nature. First step, an agent-based Pareto optimization framework was applied to discover optimal Pareto design solution for product family design. Then, post optimal

techniques were used to determine a product platform according to a single product perspective and multiple product perspectives by considering the quality loss.

To support platform identification, the degree of commonality between products in a product family has been mostly used. To measure commonality and diversity, commonality indices have been developed as metrics of measuring the degree of commonality. These indices consists of the degree of commonality index (DCI), total constant commonality index (TCCI), the commonality index (CI), the component part commonality index ($CI^{(C)}$), the product line commonality index (PCI), the percent commonality (%C), the functional similarity index (FSI), commonality versus diversity index (CDI), and comprehensive metric for commonality (CMC) [101]. Comparison of characteristics of these indices is presented in detail in reference [101]. Among these, CDI and CMC could manage information in functional and component levels to optimize the degree of commonality, while other indices were utilized for component-based commonality [102]. By integrating the CDI and CMC, the design for commonality and diversity method was proposed to identify the trade-off between commonality and diversity during whole product design process [102].

The product platform can help satisfy market niches with multiple benefits such as reduced development cost and lead time, reduced system complexity, flexible product positioning and service improvement [93, 101, 103, 104]. On the other hand, as commonality increases due to the product platform, the merit and performance of high-end products in a vertical leveraging platform strategy is sacrificed by low-end products [93]. The high commonality in a platform and/or a product family can sacrifice distinctiveness, performance, and the value of a high-end platform product in the product family [93, 101]. Thus, trade-off between commonality and diversity in the product family design has been one of the key issues. When applying the product platform to a product family, the product family has been designed by optimizing trade-offs between economic benefits and performance loss [90].

2.4.2 Product Family Design for Sustainability

To concern sustainability and product lifecycle, modular product architecture design was integrated with eco-design for developing a sustainable product family. Most of studies focused on how to redesign modular architecture for the end-of-life stage. Ji, et al. [105] proposed a leader-follower joint optimization model to improve material reuse and recycle at the end-of-life stage. To determine eco-modules, technical system modularity was considered as a leader, and material reuse modularity was considered as a follower for a bi-level optimization by using genetic algorithm. Functional and structural similarities were considered for the technical system modularity, and material reuse similarity was considered for the material reuse modularity. Yang, et al. [106] also proposed eco-modular design method to reorganize components in modules for reuse, recycle, and maintenance at the end-of-life stage. Tseng, et al. [81] introduced a modular design method to facilitate assembly and disassembly processes for the end-of-life performance by using liaison graph model and grouping genetic algorithm. After determining modular design, the modular design was evaluated by the pollution value according to material type and cost analysis. However, these studies have generated mostly a single eco-product or eco-modules rather than generating product family design based on the eco-modules for sustainability.

To extend the eco-modules and eco-product to the product family, common modules and modules for product variants should be determined. A few research considered this issue. The eco-product family was defined as “a design to improve the environmental performance of the end-of-life phase of a product family [35].” Yu, et al. [107] introduced a method based on a Quality Function Deployment (QFD) and modularity to improve end-of-life performance for a product family based on modular drivers, such as a variety of products, recyclability, and reusability. When developing QFD, eco-customer requirements and its importance weights were considered to determine values of the modular drivers. Modules were clustered by a fuzzy clustering

method based on the modular drivers. Then, module variants and common modules were distinguished by degree of module variety. However, product family configuration was not developed in the method. Yang, et al. [35] introduced an eco-product family design method to focus on end-of-life stage. Each module in the eco-product family was clustered to facilitate reuse and/or recycle processes. A grouping genetic algorithm was applied to configure the eco-product family. According to configurations of the eco product family, product platform and variants were distinguished. Wu, et al. [108] proposed a bi-objective mixed integer programming model to determine product family configuration for both new products and remanufactured products based on a trade-off between market share and costs. Wang, et al. [109] identified product family configuration based on a trade-off product family cost and greenhouse gas emission. Yan, et al. [110] investigated sustainable product conceptualization including a product platform by integrating functional, marketing, and commercial perspectives. The concept of the product platform was elicited by expert knowledge based methods like general sorting and design knowledge hierarchy. The preferred sustainable product conceptualization was selected by the rated sustainability and cost criteria from domain experts. Siddique and Rosen [111] defined a configuration of design space for a product platform and product family design mathematically by considering multiple lifecycle considerations like physical connections among components (intent design space), physical connections among modules (connections design space), and assembly sequences (assembly design space).

In previous studies for the eco-product design, a platform strategy for eco-design was not clearly considered. Therefore, to develop the eco-product family design, the new concept of a sustainable platform is needed to consider commonality with dependencies between components, and sustainability including environmental, economic, and social performances.

2.5 Limitations and Challenges

The previous works have provided a great background for carrying out design for sustainability. Most of the previous studies have focused on the impact of the product design on manufacturing and operational issues, like product assembly and product complexity. However, the previous research has limitations in five areas that require new methods to design sustainable product.

First, modular product architecture design shares the drawbacks of less considering the sustainability over product lifecycle. Most existing studies of the modular product design had identified modules to minimize product complexity for manufacturing based on physical or functional interrelationships between components. However, these studies were limited to catch and reflect the characteristics of modular design for enhancing sustainability because the research scope was focused on manufacturing. To achieve sustainable product design, a new approach that can consider the impact of product design on environmental, economic, and social aspects is required. Since the starting point of the sustainable design is to evaluate the current status of the product design and plan how to improve product design for sustainability, product design assessment methods, such as disassembly complexity and the degree of modularity for product recovery, are necessary.

Second, existing studies for product recovery have focused on the disassembly planning for minimizing disassembly costs based on predefined modules rather than configuring modules and modular architecture for the product recovery strategy. On the other hand, existing studies for modular product design have mainly focused on developing modular product architecture for manufacturing. Therefore, to fill the research gaps, a new concept of modular architecture design method is needed to reflect a product recovery strategy into product architecture design towards a sustainable product, and enhance the recyclability and reusability.

Third, since products in existing studies have been assessed from the viewpoint of manufacturing or environmental performance, a new concept of a product assessment method is needed to understand and check whether designers' intent related to sustainability has been well reflected to the product design or not. Therefore, current product assessment methods will be extended to concern sustainability and product lifecycle.

Fourth, few studies have investigated platform design for enhancing sustainability. A product platform has been developed only for identifying best trade-off between commonality and diversity for mass customization, and the best trade-off between maximizing performance and minimizing cost. Therefore, the platform design should be extended to reflect environment concern, commonality, and redesign possibility for enhancing the sustainability of a product family.

Finally, integrating eco-design and a product family has less researched. Since a variety of products should be developed to compose a product family at early product design stage simultaneously, planning product family design has a lot of potentials to fulfill customer requirements at market segments and improve sustainability. Therefore, design factors related to eco-design (e.g., environmental performance) and end-of-life recovery should be considered for the product family design.

Chapter 3. The Framework of a Sustainable Product Family Design Methodology (SPFDM)

Due to government regulation and environmental concerns, designing products requires designers to rethink and redesign the products towards more sustainable way. This chapter introduces a framework of the SPFDM to develop a sustainable product family in dynamic and uncertain market environments. Section 3.1 introduces the details of the SPFDM along with the employed methods. Section 3.2 summarizes the chapter with a recap of the proposed method, and a look ahead to implementation of the proposed method.

3.1 Sustainable Product Family Design Methodology

The principal contribution of this dissertation is to introduce a SPFDM to support both environmental friendly product design and product family design. The proposed methodology extends the concepts of modular product architecture design, product family design, and platform strategy into a sustainable product family. The steps and associated methods are elaborated in Figure 3.1.

Figure 3.1 Overview of the sustainable product family design methodology

The proposed methodology consists of five steps: 1) analyze product architecture, 2) assess product architecture for product recovery, 3) identify eco-modular architecture and strategies, 4) identify a sustainable platform, and 5) generate product variants. Various tools are used in this research to support the proposed five steps. The first step is to analyze overall product design information and constraints related to customer needs, components' dependency, and functional requirements of products. Based on fundamental information on products, product architecture is assessed to capture current product design condition quantitatively from viewpoint of disassembly in the second step. The modified entropy theory is utilized to represent a tendency of the disassembly complexity of the product architecture based on component and interface design. In the third step, a novel concept of modular architecture is identified to enhance efficiency and effectiveness of product recovery processes. Markov Cluster Algorithm is used to generate eco-modular architecture for product recovery on the basis of the disassembly complexity from the second step, interface complexity, material similarity, and lifespan similarity. In the fourth step, a new concept of a platform is introduced and identified as a component or module with high sustainability calculated by grey relational analysis, low risk to product redesign derived from change propagation analysis, and high commonality in order to develop a sustainable product family. Fuzzy inference system is used to decide which components or modules can be the sustainable platform. In the fifth step, configurations of sustainable product variants are determined based on the eco-modular architecture and the sustainable platform. The existing product family design methods are used and extended to analyzing system requirement and customer requirements for first step, defining module boundary for third step, defining common platform architecture for fourth step, and selecting product family architecture for fifth step in this study.

3.1.1 Step 1: Analyze Product Architecture

Step 1 is to obtain product data for understanding product architecture of a product in a product family and for planning sustainable product design. The first task is to describe physical and/or functional relationships in a product by using an undirected graph and design structure matrix (DSM). The graph contains nodes and edges. The node represents product components that have each design attributes, such as material composition, weight, quantity, cost, price, environmental impact, and so on. The edge represents relationships or interactions between components. The graph can be illustrated by adjacency matrix in graph theory and computer science, which is known as DSM in product design. A complexity of the graph depends on the number of nodes and edges. For example, if the number of the nodes and edges are increased, the complexity can be increased exponentially. Since the complexity is closely linked to manufacturing (assembly) and remanufacturing (disassembly) processes, designers should develop products with concerning how to minimize the complexity in early product design stage. Therefore, this step is necessary to develop and design sustainable products.

The second task is to determine component attributes based on customer requirements. The customer requirements are collected to establish target market segments and customers' preference for a new or existing product or service by conducting market survey [112] and data mining techniques [113]. Then, the customer requirements are mapped to functional requirements in engineering level for a product, service, and sustainable needs by matrix-based approaches, especially, quality function deployment (QFD) [107]. To design components and modules of products in detail, the functional requirements are translated into technical specifications of the components in the product. Therefore, for component analysis, bill of materials (BOM) is used to list the components' specifications like raw material, sub-assemblies, weights and quantities of each part, manufacturing types, and so on.

The third task is to represent functional relationships between components based on four types of interactions based on Pimmler and Eppinger [68].

- Spatial: A spatial-type interaction identifies needs for adjacency or orientation between two elements.
- Energy: An energy-type interaction identifies needs for energy transfer between two elements.
- Information: An information-type interaction identifies needs for information or signal exchange between two elements.
- Material: A material-type interaction identifies needs for materials exchange between two elements.

Regarding the four types of interactions, a functional diagram provides a way to understand comprehensive interactions together as shown in Figure 3.2. For example, a functional diagram for a product can be developed by using design information that consists of BOM and four types of interactions. Accordingly, through the functional model, decision makers can make a plan for how to enhance assemblability and disassemblability with keeping function of the product.

Figure 3.2 Functional diagram of a coffee maker

3.1.2 Step 2: Assess Product Architecture for Product Recovery

Based on information from Step 1, Step 2 of the SPFDM introduces product disassembly complexity (PDC) to quantify the difficulty of disassembly according to component and interface design. The disassembly process is necessary to achieve product recovery strategies successfully, and makes an impact on reusability and recyclability of end-of-life products. The PDC is mainly affected by following factors:

- The total number of components and interfaces
- The number of unique components and interfaces
- Design of components and interfaces for processing operations

Although assembly process for manufacturing is well automated, disassembly processes for the product recovery are manually carried out [114]. When the number of components and connections in a product are increased, the PDC also can be increased. So, each component and interface design have a critical effect on the efficiency of disassembly process. To represent and predict how difficult an operator disassembles a product, difficulty level of component and interface design is analyzed based on design for manufacturing and remanufacturing. The PDC helps designer predict the disassembly complexity of the product and then plan to redesign the product architecture by minimizing the disassembly complexity. In Chapter 4, the process of measuring the product disassembly complexity for product recovery process is described in detail.

3.1.3 Step 3: Identify Eco-modular Architecture and Strategies

After assessing individual component and interface, Step 3 proposes a novel design method to design eco-modular architecture, which is product architecture for enhancing end-of-life processes, and assess modularity in terms of the end-of-life stage. The eco-modular architecture design supports recyclability and reusability by enhancing product

architecture design. So, three sustainable modular drivers are suggested to reconfigure current product architecture towards eco-modular architecture while keeping interrelationships between components to perform functionality successfully.

- Interface complexity
- Material similarity for recycling
- Components' lifespan similarity for recycling and reusing

A clustering method, Markov Cluster Algorithm (MCL), which is an unsupervised algorithm for graphs based on simulation of flows in a graph, is applied to determine eco-modules with considering physical dependency among components based on these sustainable modular drivers. The fundamental principle of the clustering is to put neighbor components linked with high strength of coupling into a module and prune away the components linked with weak coupling strength. Alternatives of eco-modular architecture resulting from the clustering can be categorized into 1) disassembly considered architecture based on interface complexity, 2) recyclability considered architecture based on material similarity, 3) reusability considered architecture based on lifespan similarity, 4) modular architecture based on the all sustainable modular drivers, and 5) modular architecture based on product disassembly complexity from Step 2. The architectures aim to reduce disassembly process from material level decomposition to module level decomposition.

To evaluate and select the eco-modular architecture from the alternative architectures, the author proposes modularity assessment metrics to identify independent interactions between modules and the degrees of similarity within each module. In Chapter 5, the process of determining eco-modular architecture is described in detail.

3.1.4 Step 4: Identify a Sustainable Platform

After determining eco-modular architecture in a single product, the eco product should be extended to a product family based on a platform strategy for providing sufficient product variants. Most previous studies in product family design have focused on its economic benefits by sharing common components in design and manufacturing phases. Although many studies have worked on eco-design methods for a single product, researching on sustainable product family and platform design is still developing. This step emphasizes on sustainable product platform identification that is a different concept with current platform design and considers the sustainability values. The sustainable platform is a set of components and/or modules that have high sustainability value, low risk to be redesigned when changing design of neighbor system propagates, and commonality of products in a product family. When it comes to understanding the degree of sustainability in a product family, three sustainability aspects such as environmental, economic, and social aspects are aggregated to a single sustainability value of a product by using multi attribute decision making approach. It helps designers compare which products are more sustainable. In order to quantify robustness of components under uncertainty of product redesign, the risk is introduced to estimate how much manufacturers will cost while redesigning current product towards sustainable products. This is because constituents of products are intricately connected to perform functionality. For example, if a platform has high commonality but high risk, the design change of the platform can influence design change of modules of entire products in a product family. Accordingly, when determining a sustainable platform, the risk of change propagation should be considered with the commonality of the platform. For modelling dependencies, Bayesian network is utilized to estimate the likelihood of components and update the likelihood of all linked components when components in a product family are redesigned. Fuzzy inference system is used to provide a basis of how characteristics of components can be decided, and determine a sustainable platform

based on the sustainability, commonality, and risk values. In Chapter 6, the process of determining eco-modular architecture is described in detail.

3.1.5 Step 5: Generate a Sustainable Product Family

Based on the sustainable platform, in Step 5, a sustainable product family can be developed to support a variety of markets and reduce environmental impacts. A method for identifying sustainable product family configuration is proposed by integrating eco-design and product family design simultaneously. The sustainable product family can contribute to making profits and reducing environmental impact by reusing and sharing remanufactured modules between products in a family at the end-of-life stage. The sustainable platform from Step 4 is applied to enhance the sustainability of a product family for the manufacturing stage. However, reusability of modules from end-of-life (EOL) products plays a key role in enhancing sustainability by saving costs and environmental impact while prolonging product lifecycle. Therefore, the sustainable platform from Step 4 and modular design are extended to an EOL platform that is focused on compatibility for reusing used modules of EOL products in this Step 5. In order to determine the EOL platform for enhancing reusability, compatibilities between products are analyzed to support the sustainable product family design in terms of physical size, function, and interface. In this step, a multiobjective design optimization model is introduced to maximize profits and minimize the environmental impact with satisfying reliability of a product. Three design information are considered to support objectives in this step.

(1) Profits (economic aspect): Remanufacturing process is important to prolong product lifecycle by reusing modules/components. Accordingly, the author considers profits from new products and remanufactured products. In terms of profits of the remanufactured products, a profit model is developed based on the remanufacturing process.

(2) Environmental impact (environmental aspect): A sustainable product must have less impact on the environment. Environmental impact of new products can be estimated by current LCA tools based on material types and its manufacturing processes. When reusing the modules that are recovered or using recycled materials for manufacturing new modules, it is able to omit several stages of the product lifecycle, so that the environmental impact can be reduced. To reflect it in product design, environmental impact is considered as one of the objectives.

(3) Customer preference (social aspect): The goal of a product family is to satisfy a variety of market segments. Accordingly, customer preference of the product family with new and remanufactured products is considered. The customer preference is also used to predict estimated demand for a sustainable product family. The expected demand is calculated by a multinomial logit choice model based on the customer preference.

In Chapter 7, the process of determining the sustainable product family is described in detail.

3.2 Summary and Preview

The SPFDM has been introduced to support sustainable product design and product family design by considering product lifecycle. In summary, the role of the chapter is to:

- Step 1: Analyze product architecture
- Step 2: Assess product disassembly complexity
- Step 3: Identify eco-modular architecture
- Step 4: Identify a sustainable platform
- Step 5: Generate a sustainable product family

The SPFDM can help a sustainable product family design strategy by integrating product architecture design and sustainability performance, such as environmental,

economic, and social performances. The next chapter illustrates the assessment method of product disassembly complexity with case studies.

Chapter 4. Product Disassembly Complexity Assessment

As Step 2 in the SPFDM, this chapter introduces product complexity assessment to quantify the difficulty of disassembly depending on component design and interface design that are closely linked to an efficiency of product recovery. Section 4.1 describes an overview of the product disassembly complexity assessment. The results from Step 1 provide basic product information including the lists and weights of components, and the list of interfaces, and so on. The information from Step 1 is utilized to calculate the product disassembly complexity with a proposed mathematical model in Section 4.2. In Sections 4.3 and 4.4, case studies with two product families are conducted to evaluate the proposed assessment method. Section 4.5 provides a summary of this chapter and a preview of the next chapter.

4.1 Overview of Product Disassembly Complexity Assessment

Product recovery highly depends on how to design a product [115]. Accordingly, consideration of the product recovery in design stage is needed to enhance product recovery processes by giving recovery potentials to a product. To enhance the product recovery processes, the disassembly should be concerned in product design. The disassembly is a systematic method for detaching materials, components, sub-assemblies (modules) from a product. The disassembly process can be to separate the product fully into material or component levels, or separate selectively the product into sub-assembly levels according to product architecture. Therefore, the disassembly process is closely related to minimizing resources, e.g., cost and time, and avoiding damage to components and sub-assemblies during the disassembly process. Also, the more complex a product or system is, the more expensive and risky product design process is. Therefore, measuring and understanding the complexity is very important for whole product development procedure. This chapter proposes a method to assess a

product disassembly complexity (PDC) that is information on how difficult a product is to disassemble for developing sustainable product design. For assessing the product disassembly complexity, the proposed method utilizes the modified entropy theory considering the number of components and interfaces, component complexity, and interface complexity. The component and interface complexities are measured by various factors from design for assembly and disassembly. The result from the proposed method contributes to comparing the degree of disassembly difficulty between products and benchmarking well-designed products to plan selective disassembly for product recovery. Also, it helps understand which components or modules are difficult to disassemble during disassembly processes.

4.2 A Method for Assessing Disassembly Complexity

Design for disassembly (DfD) is the design process of designing products to separate components easily and cost effectively. The purpose of DfD is to take less time to disassemble and then minimize disassembly cost. In many approaches, precedence matrix and graph representation were applied to determine optimal disassembly sequences. However, this study considered a ‘product disassembly complexity’ term that is defined as the degree of disassembly difficulty due to design information on components and interfaces. The notion of complexity has two levels: component and interface complexities. Based on the two levels, information on disassembly related attributes is introduced to quantify the complexity in Figure 4.1.

Figure 4.1 Levels of complexity for design for disassembly

For the component complexity, it emphasizes on attributes related to handling components. It can be further divided into component attributes that are represented by four factors: weight effect factor, size, symmetry, and grasping components.

(1) *Weight effect factor*: The weight effect factor represents how difficult components are positioned and handled according to component weight. Components with heavy weight would reduce assembly accuracy and need more man powers, extra tools like lift, and set-up time for components and tools. When the weight effect factor is equal to 1, it means that the component weight highly affects operators to assemble the component while an assembly process.

(2) *Size factor*: A component size has an impact on both assembly and disassembly operations. When the component size is too small to grab it, it can delay the disassembly process.

(3) *Symmetry factor*: The symmetry factor represents the difficulty of positioning components for reassembly after disassembling and then recovering the components. Symmetry of a component is also particularly influenced on feeding the component. The symmetry properties consist of symmetry and asymmetry. As for the symmetry that has more advantages than the asymmetry, there are two types of the symmetry: alpha and beta symmetries. Alpha symmetry is the rotation symmetry around an axis that is

perpendicular to the assembly direction [116, 117]. The value of alpha is the smallest angle when rotating the component about the axis to position the correct assembly direction. Beta symmetry is the rotation symmetry in an axis along the assembly direction. The value of beta is the smallest angle when rotating the component about the axis along the assembly direction to position the correct assembly direction.

(4) *Grasping and manipulation*: Difficulty of grasping components has highly impact on feeding and handling components. Material property plays an important role in grasping components, especially vulnerability and stiffness. Vulnerability entails damages or deformation of components by dropping, bumping, and excessive grabbing force. The vulnerability is related to the quality of components. When replacing used components, the vulnerability should be an issue. Stiffness is the rigidity to resist deformation in response to an applied force, which is represented by elasticity modulus. A material with high stiffness is not flexible but assembly-friendly. Instead, a material with a low elasticity modulus is more flexible. As a component with low vulnerability and high stiffness can be easily grasped by a worker, it would improve assembly efficiency and minimize assembly time. However, in this study, vulnerability and stiffness are simplified as ‘easy and not easy’.

For interface complexity, the connector between components is a key element for manual disassembly operations because the connector links components’ geometric and functional relationships through material, energy, and signal flows. There are three attributes of the connectors for disassembly: mechanical connector types, non-mechanical connector types that would help strongly to attach components, and an intensity of tool use. These attributes are critical to detach components or modules from a product.

(1) *Mechanical connectors*: The mechanical connectors are mostly used in product assembly. As the mechanical connectors are detachable fasteners with relevant tools, it can be recursive for assembly and disassembly. In this research, nine types of the mechanical connectors are considered as follows: screw/bolt with standard head,

screw/bolt special head, nut and bolt, retaining ring/circlips, interference fit, rivets/staples, pin, cylindrical snap fit, and cantilever snap fit.

(2) *Non-mechanical connectors*: The non-mechanical connectors are to firmly bond components, so that disassembly can be mostly difficult. When the connectors are used in assembly processes, additional chemical materials like lead and welding material, to name a few, are needed. If operators want to disassemble and then reassemble for reusing components, the components have high chance to be damaged during disassembly.

(3) *Intensity of tool use*: When using the mechanical and non-mechanical connectors, relevant tools are needed for assembly and disassembly operations. There are many difficulties of tool usage because of spatial constraints, assembly/disassembly angle, intensity when using tools, and the number of necessary tools. As the intensity is closely related to disassembly efficiency of operators, the number of tools for disassembling components and the intensity of the tool use are considered as a disassembly attribute to represent the difficulty of assembly.

These attributes, descriptions, and difficulty factors for components and interfaces are represented in Table 4.1. For the component complexity, difficulty factors were determined by measuring assembly handling time and normalizing it based on Samy and ElMaraghy [118]. For the interface complexity, U-rating values were applied to measure mechanical and non-mechanical unfastening processes. The U-rating value was developed to estimate disassembly efforts based on a survey by Das and Naik [119] and Das, et al. [120]. Since the range of the U-rating value was not between 0 and 1, the U-rating value was normalized in this study. Consequently, the difficult factors for the complexities are shown in Table 4.1.

Table 4.1 Disassembly attributes for manual disassembly

Group	Attribute	Description	Difficulty factor
Component	Weight	<4.5kg	0.50
		>4.5kg	1.00
	Size	>15mm	0.74
		6mm to 15mm	0.81
		<6mm	1.00
	Symmetry($\alpha+\beta$)	<360	0.70
		$360 \leq \alpha+\beta \leq 540$	0.84
		$540 < \alpha+\beta \leq 720$	0.94
		=720	1.00
	Grasping and manipulation	Easy	0.91
		Not easy	1.00
Interface	Mechanical unfastening process (U-rating)	Screw/bolt standard head	0.35
		Screw/bolt special head	0.55
		Nut and bolt	0.53
		Retaining ring/circlips	0.63
		Interference fit	0.45
		Rivets/Staples	0.50
		Pin	0.45
		Cylindrical snap fit	0.40
		Cantilever snap fit	0.33
	Non-mechanical unfastening (U-rating)	Welding process	1.00
		Adhesive	0.53
	Tools required with low intensity/ high intensity	1	0.3/0.4
		2 (sequential use for a part)	0.6/0.8
		More than 2	1.00/1.00

Based on the aforementioned information, a model of the product disassembly complexity was introduced in this study. The PDC was modified from a method of product assembly complexity that was proposed by Samy and ElMaraghy [118]. The product assembly complexity method focused on assessing whole product complexity in terms of assembly processes by aggregating the complexity indices of various components.

In order to extend the product assembly complexity to the product disassembly complexity, the difficulty factors are assessed from the viewpoint of disassembly operations. Furthermore, the number and types of interfaces with its difficult factors are considered for this proposed model because the connections between modules/components are critical for disassembly operations.

The proposed method for the PDC is modelled as shown in below:

$$PDC = \left(\frac{n_c}{N_c} + CI \right) \log_2 (N_c + 1) + \left(\frac{n_i}{N_i} + II \right) \log_2 (N_i + 1) \quad (4.1)$$

Where N_c and N_i are the number of components and connectors, respectively; n_c and n_i are the number of unique components and connectors in the product; and CI is component complexity index and II is interface complexity index.

The basic concept of this equation (4.1) is modified based on an equation of the entropy theory. The entropy is the expected value of the information under uncertainty, and represents unpredictability of information contents. For example, when there is no way to predict the outcome according to less information, the entropy is the highest, which is 1. When the outcome is predictable, the entropy is closed to 0. By modifying the entropy theory, the PDC aims to represent a tendency of disassembly complexity logarithmically according to N_c , N_i , CI , and II . In terms of CI and II , it helps designers understand disassembly difficulty that is caused by how to design components and interfaces. Design guidelines for assembly and disassembly [34, 62] suggested that the number of components and interfaces in a product are closely related to the product complexity for disassembly.

In order to understand the PDC changes according to input information changes, sensitivity analysis is performed. Figure 4.2 (a) represents the PDC increase when information on components (N_c , n_c , and CI) is increasing, while Figure 4.2 (b) shows the PDC increase according to a rise in information on interfaces (N_i , n_i , and II). The high value of the PDC means that more efforts are required to disassemble products to sub-assembly level or single component level.

(a) Variation of PDC when changing information on components

(b) Variation of PDC when changing information on interfaces

Figure 4.2 Variation of PDC when changing information on components and interfaces

4.2.1 Component Complexity Index

Difficulty factors of each component could be examined based on four attributes, such as weight ($C_{c,1}$), size ($C_{c,2}$), symmetry ($C_{c,3}$), and grasping and manipulation ($C_{c,4}$) as shown in Table 4.1. Component complexity index (CI) is calculated by following equations:

$$C_k = \frac{\sum_{j=1}^J C_{c,j}}{J} \quad (4.2)$$

$$CI = \sum_{k=1}^{n_p} w_k C_k \quad (4.3)$$

$$w_k = \frac{p_k}{N_c}, \quad \sum_{k=1}^{N_p} w_k = 1 \quad (4.4)$$

Where, C_k is a complexity of k th component; $C_{c,j}$ is a difficulty factor value of the j th attributes; J is the number of attributes for component complexity (here, $J=4$); w_k is a percentage of dissimilarity of k th component that makes total CI set between 0 and 1; and p_k is the number of k th component. If the component is unique, p_k could be one. CI for a product can be calculated as equation (4.4).

4.2.2 Interface Complexity Index

The connector is a key element of the interface to link components' geometric and functional relationships through material, energy, and signal flows. Therefore, difficult of mechanical connector ($C_{i,1}$), non-mechanical connector ($C_{i,2}$), and intensity of tool use ($C_{i,3}$) were utilized to measure interface complexity as shown in Table 4.1. Single interface complexity index of k th component, I_k , is calculated as follow:

$$I_k = \frac{\sum_{n=1}^N C_{i,n}}{N} \quad (4.5)$$

$$II = \sum_1^{n_p} w_k I_k \quad (4.6)$$

Where, $C_{i,n}$ is a difficult factor value of n th interface attributes from Table 4.1, and N is the number of attributes for evaluating the interface attributes. Interface complexity index (II) is calculated as equation (4.6). Consequently, CI and II are applied to equation (4.1) for calculating the product disassembly complexity.

4.2.3 A Single Component Complexity Index

The PDC focused on assessing component complexity and interface complexity for product, respectively. However, when assessing a single component or a module design, the PDC has a difficulty of representing a complexity of a single component and module design. This is because the single component contains the component design itself as well as interface design. Accordingly, the component design and interface design of a corresponding component should be considered at the same time for assessing the single component. Therefore, the CI and II were applied to quantify complexity for a single component and/or a module without considering the number of constituents in a product as shown in equation (4.1). For determining a single component complexity index ($SCCI$) of k th component, the weighted average value was applied to consider of component and interface complexity indices simultaneously as shown in following equation:

$$SCCI_k = \frac{C_k \sum_1^J C_{c,j} + I_k \sum_1^N C_{i,n}}{\sum_1^J C_{c,j} + \sum_1^N C_{i,n}} \quad (4.7)$$

Where, C_k is the average of difficulty factors for components, and I_k is the average of difficulty factors for interfaces from equations (4.2) and (4.5). Based on the $SCCI$ that

represents complexity of each component in a product, it can be applied to identify the selective disassembly paths with less disassembly complexity for separating target components and/or modules.

4.2.4 Evaluation of Product Architecture

According to the proposed method, product architecture can be quantitatively evaluated with different level of product architecture, such as complexity of component level, module level, and product level, as followings:

(1) Complexity of individual component and interface

Based on the difficulty factors in Table 4.1, designers can know complexities of each component ($C_{c,j}$) and each interface ($C_{i,n}$). The complexities represent whether or not designers consider disassembly processes when designing the components and interfaces.

(2) Complexity of modules

Since modules contain components and its interfaces, designers can evaluate modules' complexity by considering both components and interfaces in the modules based on equation (4.7).

(3) Complexity of selective disassembly

A difficulty of the selective disassembly is caused by component design and interface design. After identifying possible disassembly sequences, designer can evaluate and compare each step of the sequences based on equation (4.7).

(4) Complexity of entire components and interfaces in a product

The component complexity (CI) and interface complexity (II) evaluate difficulties from all components and interfaces in the product, respectively.

(5) Complexity of a product for disassembly

Designers can evaluate the complexity of a product with considering CI, II, and the number of components, unique components, interfaces and unique interfaces based on equation (4.1).

4.3 Case Study I: Electric Shavers

The case study is performed to demonstrate the effectiveness of proposed method. Philips electric shavers in a product family, AT600 and AT750, were disassembled to assess their disassembly complexity. AT600 in Figure 4.3 is a low-end model with cheap price in the product family, while AT750 in Figure 4.4 is a high-end model. These two products have similar architecture to perform main functions as electric shavers. However, the low-end and high-end products have a different design of components and interfaces according to design strategies of a company. Furthermore, the different design leads to different disassembly difficulty depending on how designers consider design for disassembly during product design and development processes. In this sense, AT600 and AT750 were selected to evaluate and compare the degree of disassembly complexity.

Figure 4.3 An explosive view of AT600

Figure 4.4 An explosive view of AT750

The component complexity of AT600 was measured as shown in Table 4.2 and interface complexity index was shown in Table 4.3. As a result, the component complexity index of AT600 is 0.770 and the interface complexity index is 0.200. Here, the number of components, N_c , is 26 and the number of unique components, n_c , is 22. When assessing the interface complexity of a single component, most of components were interlocked with snap fit type and structural restriction. The snap fit type connector could be disassembled without tools. So, their difficulty factors of required tools were 0. For this reason, the snap fit type connector was not counted in N_i but connections with some materials like screws, pins, adhesive, and welding/soldering were counted. For AT600, seven interfaces which included pins for three components and soldering for four components were needed to remove. So, the number of unique interface (n_i) was two. As a result, the product disassembly complexity of the AT600 was 9.142.

Table 4.2 Component complexity index of AT600

Component name	#No.	Weight (g)	Size	Sym.	Grasp	J	SUM	C _k	w _k	w _k ·C _k
Upper blade cover	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Blade cover	2	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.08	0.06
Blade	2	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.08	0.06
Blade holder	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Main body cap	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
On/off spring	1	0.50	0.81	0.84	1.00	4.00	3.15	0.79	0.04	0.03
On/off button	1	0.50	1.00	0.84	1.00	4.00	3.34	0.84	0.04	0.03
Gear module	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Secondary gear	3	0.50	0.81	0.70	0.91	4.00	2.92	0.73	0.12	0.08
Main motor gear	1	0.50	1.00	0.84	1.00	4.00	3.34	0.84	0.04	0.03
Gear module cover	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Top outer casing	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
LED power cap	1	0.50	1.00	0.84	1.00	4.00	3.34	0.84	0.04	0.03
Microswitch cover	1	0.50	0.81	0.84	1.00	4.00	3.15	0.79	0.04	0.03
Microswitch cover support	1	0.50	1.00	0.70	1.00	4.00	3.20	0.80	0.04	0.03
Inner body housing	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
Motor	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Printed circuit board	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Battery	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Charging pin connectors	1	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.04	0.03
Rubber ring	1	0.50	0.74	0.70	1.00	4.00	2.94	0.74	0.04	0.03
Bottom casing	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
CI										0.770

Table 4.3 Interface complexity index of AT600

Component name	#No	Mech.	Non-mech.	Tool	N	SUM	I _k	w _k	w _k ·I _k
Upper blade cover	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Blade cover	2	0.40	0.00	0.00	3.00	0.40	0.133	0.08	0.010
Blade	2	0.40	0.00	0.00	3.00	0.40	0.133	0.08	0.010
Blade holder	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Main body cap	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
On/off spring	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
On/off button	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Gear module	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Secondary gear	3	0.45	0.00	0.00	3.00	0.45	0.150	0.12	0.017
Main motor gear	1	0.45	0.00	0.30	3.00	0.75	0.250	0.04	0.010
Gear module cover	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Top outer casing	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
LED power cap	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Microswitch cover	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Microswitch cover support	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Inner body housing	1	0.33	0.00	0.00	3.00	0.33	0.110	0.04	0.004
Motor	1	0.40	1.00	0.40	3.00	1.80	0.600	0.04	0.023
Printed circuit board	1	0.00	1.00	0.40	3.00	1.40	0.467	0.04	0.018
Battery	1	0.40	1.00	0.40	3.00	1.80	0.600	0.04	0.023
Charging pin connectors	1	0.00	1.00	0.40	3.00	1.40	0.467	0.04	0.018
Rubber ring	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
Bottom casing	1	0.40	0.00	0.00	3.00	0.40	0.133	0.04	0.005
II									0.200

In the same way, AT750 model was assessed as shown in Table 4.4 and Table 4.5. The AT750 has 26 components, 17 unique components, 8 interface types with pins for 5 components and soldering for 3 components, and 2 unique interface types. The component complexity index was 0.767 and the interface complexity index was 0.189. Finally, product disassembly complexity of the AT750 was 8.149.

Although two products had similar component and interface complexities, AT750 was less complex about 10.7% than AT600 in Table 4.6. There are two reasons. (1) The number of unique components: AT750 had less unique components rather than AT600. AT600 had 22 unique components, while AT750 had 17 unique components. When increasing the number of unique components, corresponding component complexity has to be added for calculating the component complexity index. Accordingly, the additional complexity index of unique components in AT600 makes higher complexity index than AT750. However, as N_c of two products was the same and each component design in two products is similar, the component complexity of these products was almost same. (2) The number of unique interfaces: AT750 had 8 connectors. However, there were two different types of connectors. On the other hand, AT600 was disassembled with 7 connectors, while three different connectors were used. Although the number of connectors in AT600 was smaller than the number for AT750, another different type of the connector in AT600 was added to the calculation of the interface complexity.

Consequently, the case study resulted that AT750 was well designed by considering design for disassembly, compared to AT600. The case study can prove that the proposed method is effectively applied to measure real products by considering component and interface complexities simultaneously. Moreover, the proposed method reflects the difference of the product disassembly complexity according to the change of the number of components and interfaces.

Table 4.4 Component complexity index of AT750

Component name	#No.	Weight (g)	Size	Sym.	Grasp	J	SUM	C _k	w _k	w _k ·C _k
Upper blade cover	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Blade cover	3	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.12	0.09
Blade	3	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.12	0.09
Blade holder	1	0.50	0.74	0.70	0.91	4.00	2.85	0.71	0.04	0.03
Upper body cap	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Gear module	1	0.50	0.74	0.70	0.91	4.00	2.85	0.71	0.04	0.03
Secondary gear	4	0.50	0.81	0.84	0.91	4.00	3.06	0.77	0.15	0.12
Main motor gear	1	0.50	1.00	0.84	1	4.00	3.34	0.84	0.04	0.03
Gear module cover	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
Inner body housing	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
Motor	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Printed circuit board	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Battery	1	0.50	0.74	0.84	0.91	4.00	2.99	0.75	0.04	0.03
Inner body housing cover	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
External body cover(f)	3	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.12	0.09
External body cover (b)	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
External body cover	1	0.50	0.74	1.00	0.91	4.00	3.15	0.79	0.04	0.03
CI										0.767

Table 4.5 Interface complexity index of AT750

Component name	#No.	Mech.	Non-mech.	Tool	N	SUM	I _k	w _k	w _k ·I _k
Upper blade cover	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Blade cover	3	0.40	0.00	0.00	3.00	0.40	0.13	0.12	0.02
Blade	3	0.40	0.00	0.00	3.00	0.40	0.13	0.12	0.02
Blade holder	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Upper body cap	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Gear module	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Secondary gear	4	0.45	0.00	0.00	3.00	0.45	0.15	0.15	0.02
Main motor gear	1	0.45	0.00	0.30	3.00	0.75	0.25	0.04	0.01
Gear module cover	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Inner body housing	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
Motor	1	0.40	1.00	0.40	3.00	1.80	0.60	0.04	0.02
Printed circuit board	1	0.00	1.00	0.40	3.00	1.40	0.47	0.04	0.02
Battery	1	0.40	1.00	0.40	3.00	1.80	0.60	0.04	0.02
Inner body housing cover	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
External body cover(f)	3	0.40	0.00	0.00	3.00	0.40	0.13	0.12	0.02
External body cover (b)	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
External body cover	1	0.40	0.00	0.00	3.00	0.40	0.13	0.04	0.01
II									0.189

Table 4.6 Results of product disassembly complexity for the electric shavers

Product family	N _c	n _c	N _i	n _i	CI	II	PDC
AT600	26	22	7	2	0.770	0.200	9.142
AT750	26	17	8	2	0.767	0.189	8.149
%complexity reduction							-10.7%

Table 4.7 shows a single component complexity index of k th component ($SCCI_k$). A scenario was assumed to explain the SCCI. Designer's target components were a battery of AT600 for reuse. So, the battery should be removed from circuit module. To simplify disassembly sequences, a possible disassembly sequence in a module level is represented as shown in Figure 4.5. Each disassembly step had the SCCI when separating components from main body and modules. Therefore, the SCCI of AT600 when separating the battery could be calculated as 2.11 by summing values of the SCCI from each disassembly step in Figure 4.5. The SCCI of AT750 was the same as AT600 because the product architecture including the components and interfaces in two products are almost the same.

Figure 4.5 Selective disassembly procedures and its complexity when removing the battery

Table 4.7 A single component complexity index of two products in a Family

AT600		AT700	
Component name	SCCI _k	Component name	SCCI _k
Upper blade cover	0.65	Upper blade cover	0.65
Blade cover	0.67	Blade cover	0.67
Blade	0.67	Blade	0.67
Blade holder	0.65	Blade holder	0.62
Main body cap	0.69	Upper body cap	0.65
On/off spring	0.69	Gear module	0.62
On/off button	0.74	Secondary gear	0.67
Gear module	0.65	Main motor gear	0.72
Secondary gear	0.63	Gear module cover	0.69
Main motor gear	0.72	Inner body housing	0.69
Gear module cover	0.65	Motor	0.72
Top outer casing	0.69	Printed circuit board	0.66
LED power cap	0.74	Battery	0.72
Microswitch cover	0.69	Inner body housing cover	0.69
Microswitch cover support	0.70	External body cover(f)	0.69
Inner body housing	0.70	External body cover (b)	0.69
Motor	0.72	External body cover	0.69
Printed circuit board	0.66		
Battery	0.72		
Charging pin connectors	0.67		
Rubber ring	0.64		
Bottom casing	0.69		

4.4 Case Study II: Coffee Makers

Another case study was carried out with two coffee makers. Philips coffee makers in a product family, HD7450 and HD7458, were analyzed to know disassembly complexity. HD7450 is a model with reasonable price for home use, while HD7458 is a model with the expensive price for the office use. The specification of these models is represented in Table 4.8. Almost all functions of constituents of these coffee makers are the same, but HD7458 has a larger capacity than HD7450. Like the previous case study with electric shavers, when disassembling the coffee makers, HD7458 was easy to disassemble, so that its disassembly efforts and time were less than HD7450. However, since it is difficult to quantify the design differences between the coffee makers, the case study has been performed with the coffee makers to identify the difference from the viewpoint of disassembly.

Table 4.8 Specifications of these coffee makers

	HD7450	HD7458

Price	S\$42	S\$89
Brewing time	< 10 minutes	< 10 minutes
Specification	220V, 50Hz, 650W 4-6 Cups (0.6 litres)	220V, 50Hz, 650W 4-15 Cups (1.3 litres)

Component complexity of HD7450 was measured in Table 4.9 and interface complexity was shown in Table 4.10. The number of components, N_c , is 18 and the number of unique components, n_c , is 15. The component complexity index of HD7450 is 0.741 based on the four attributes. Here, three different types of screws were used to assemble components ($N_i=3$), and total eight screws ($n_i=8$) were used to assemble between a bottom cover and bottom casing with 4 screws, between a casing for heater and heater with 3 screws, and between a glass cup and handle of a decanter with 1 screw. Therefore, a difficult factor of tools for these components has a value with 0.3 because of requiring the use of a screw driver. For other components, since they were assembled by snap-fit and interference fit, tools were not required. Table 4.11 shows a single component complexity index ($SCCI_k$) of HD7450.

Table 4.9 Component complexity of a coffee maker (HD7450)

Component name	#No.	Weight (g)	Size	Sym.	Grasp	J	SUM	C _k	w _k	w _k ·C _k
Bottom cover	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Silicon ring	1	0.50	0.81	1.00	1.00	4	3.31	0.828	0.06	0.046
Hot plate	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Casing for heater	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.040
Heater	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Power cord	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Water tube set	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Silicon tube	4	0.50	0.74	0.70	0.91	4	2.85	0.713	0.22	0.158
Water reservoir	1	0.50	0.74	1.00	0.91	4	3.15	0.788	0.06	0.044
Steam sprout	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.040
Filter basket	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
Filter	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.040
Lid of coffee maker	1	0.50	0.74	1.00	0.91	4	3.15	0.788	0.06	0.044
Decanter	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.040
Bottom casing	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.042
CI										0.741

Table 4.10 Interface complexity of a coffee maker (HD7450)

Component name	#No.	Mech.	Non-mech.	Tool	N	SUM	I _k	w _k	w _k ·I _k
Bottom cover	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.012
Silicon ring	1	0.45	0.53	0.00	3.00	0.98	0.327	0.06	0.018
Hot plate	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.012
Casing for heater	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.012
Heater	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.008
Power cord	1	0.45	1.00	0.00	3.00	1.45	0.483	0.06	0.027
Water tube set	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.008
Silicon tube	4	0.45	0.00	0.00	3.00	0.45	0.150	0.22	0.033
Water reservoir	1	0.33	0.00	0.00	3.00	0.33	0.110	0.06	0.006
Steam sprout	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.008
Filter basket	1	0.10	0.00	0.00	3.00	0.10	0.033	0.06	0.002
Filter	1	0.10	0.00	0.00	3.00	0.10	0.033	0.06	0.002
Lid of coffee maker	1	0.40	0.00	0.00	3.00	0.40	0.133	0.06	0.007
Decanter	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.012
Bottom casing	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.012
II									0.181

Table 4.11 A single component complexity index of HD7450

HD7450	
Component name	SCCI _k
Bottom cover	0.011
Silicon ring	0.015
Hot plate	0.011
Casing for heater	0.010
Heater	0.011
Power cord	0.016
Water tube set	0.011
Silicon tube	0.010
Water reservoir	0.011
Steam sprout	0.010
Filter basket	0.010
Filter	0.009
Lid of coffee maker	0.011
Decanter	0.010
Bottom casing	0.011

In the same way, HD7458 model was assessed. The component complexity is 0.740 as shown in Table 4.12, while the interface complexity of HD7458 is 0.183 as shown in Table 4.13. HD7450 has 17 components ($N_c = 17$), 14 unique components ($n_c = 14$), 4 interface types with two different types of screws ($N_i = 4$, $n_i = 2$). The index of product disassembly complexity of HD7458 was 8.105.

As a result, in Table 4.14, complexity indices of component and interface were slightly different because these two products have similar product architecture and components to perform the same functions. However, the N_c , n_c , N_i , and n_i would give rise to more differences of the PDC between two coffee makers about 4.1%.

Table 4.12 Component complexity of a coffee maker (HD7458)

Component name	#No.	Weight (g)	Size	Sym.	Grasp	J	SUM	C _k	w _k	w _k ·C _k
Bottom cover	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Heater clip	1	0.50	0.74	1.00	0.91	4	3.15	0.788	0.06	0.046
Hot plate	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Casing for heater	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.042
Heater	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Power cord	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Water tube set	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Silicon tube	4	0.50	0.74	0.70	0.91	4	2.85	0.713	0.24	0.168
Water reservoir	1	0.50	0.74	1.00	0.91	4	3.15	0.788	0.06	0.046
Steam sprout	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.042
Filter basket	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
Lid of coffee maker	1	0.50	0.74	1.00	0.91	4	3.15	0.788	0.06	0.046
Decanter	1	0.50	0.74	0.70	0.91	4	2.85	0.713	0.06	0.042
Bottom casing	1	0.50	0.74	0.84	0.91	4	2.99	0.748	0.06	0.044
CI										0.740

Table 4.13 Interface complexity of a coffee maker (HD7458)

Component name	#No.	Mech.	Non-mech.	Tool	N	SUM	I_k	w_k	$w_k \cdot I_k$
Bottom cover	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.013
Heater clip	1	0.63	0.00	0.00	3.00	0.63	0.210	0.06	0.012
Hot plate	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.013
Casing for heater	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.013
Heater	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.009
Power cord	1	0.45	1.00	0.00	3.00	1.45	0.483	0.06	0.028
Water tube set	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.009
Silicon tube	4	0.45	0.00	0.00	3.00	0.45	0.150	0.24	0.035
Water reservoir	1	0.33	0.00	0.00	3.00	0.33	0.110	0.06	0.006
Steam sprout	1	0.45	0.00	0.00	3.00	0.45	0.150	0.06	0.009
Filter basket	1	0.10	0.00	0.00	3.00	0.10	0.033	0.06	0.002
Lid of coffee maker	1	0.40	0.00	0.00	3.00	0.40	0.133	0.06	0.008
Decanter	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.013
Bottom casing	1	0.35	0.00	0.30	3.00	0.65	0.217	0.06	0.013
II									0.183

Table 4.14 Results of the product disassembly complexity for the coffee makers

Product family	N_c	n_c	N_i	n_i	CI	II	PDC
HD7450	18	15	8	3	0.741	0.181	8.449
HD7458	17	14	4	2	0.740	0.183	8.105
%complexity reduction							-4.1%

4.5 Summary and Preview

The disassembly operations are closely related to the efficiency of reusability and recyclability in the end-of-life stage of products. Accordingly, it is necessary to understand and estimate disassembly difficulty of current product design for developing sustainable products. A method was proposed to identify product disassembly complexity that is information on how difficult a product is to disassemble for enhancing recyclability and reusability. For assessing the disassembly complexity for products, various design information was utilized to measure component design and interface design. The proposed method considered various disassembly attributes from design for assembly and disassembly, and the number of components and interfaces. In order to demonstrate the proposed method, case studies with families of electric shavers and coffee makers were performed.

The proposed method contributes to representing a complexity of product design from the viewpoint of disassembly and determining disassembly paths with less complex components and interfaces. Moreover, it would help develop design strategies and benchmark product design for better product architecture design for product recovery. In this sense, the proposed method can be a starting point to enhance the sustainability of products.

However, it was challenging to decide the range of the complexity like not complex, normal, complex, or very complex. More case studies with complex products will be performed to decide the range of the complexity and validate the proposed method. The proposed method didn't consider the effects of a platform strategy in a product family. Accordingly, future work will be performed to decide the range of the complexity, and consider the effects of the platform strategy when assessing product family complexity for disassembly.

The next chapter provides a new concept of a modular architecture for enhancing reusability and recyclability. Sustainable modular drivers and modularity assessment method for product recovery are introduced for developing and assessing the new concept of modular architecture. A clustering algorithm based on graph theory is applied to determine the modular architecture.

Chapter 5. Eco-modular Product Architecture Identification and Assessment for Product Recovery

This chapter as Step 3 in the SPFDM introduces a method to determine how product recovery affects modular product architecture and how the architecture should be assessed from the viewpoint of the end-of-life stage of product lifecycle. Section 5.1 describes the overview of the modular architecture design methods. A process of the proposed design method is represented in Section 5.2. Based on the product information from Step 1, component based DSM is developed to represent dependency between components in Section 5.3 and is the fundamental background for developing the eco-modular architecture. In order to organize product architecture in terms of product recovery, sustainable modular drivers are introduced in Section 5.4. The sustainable modular drivers consist of interface complexity, material similarity, and lifespan similarity. Based on the sustainable modular drivers, Markov Cluster Algorithm is used to group components with similar characteristics into modules in Section 5.5. Additionally, physical relationships in the DSM, and the product disassembly complexity from Chapter 4 is applied to generate alternatives of eco-modular architectures in Section 5.7.3. To assess newly proposed modular architecture, modularity assessment for the EOL stage is introduced in Section 5.6.

5.1 Overview of Modular Architecture Design Method

With the rapid development of technology, high-end products, especially electronic products, incite customers to purchase goods without thinking of the impact it will have on the environment. The technology push strategy of a company results in mass production of new products and frequent product replacements by the customers. The mass production for new products increases the impact on environmental pollution during the manufacturing process. Although a product is still good enough to use, when

the product is discarded, the product lifecycle shortens. This has a negative effect on the environment as the landfill rate heightens. Therefore, product recovery must be considered in the early product design stage to minimize the landfill rate.

To recover products in the end-of-life (EOL) stage, product architecture development is necessary to facilitate the disassembly process. If product architecture is complex at the disassembly stage, individual components of the product can be difficult to retrieve and can increase the chances of damage [55, 61]. In this sense, modular product design should be one of the most important considerations to improve disassemblability for the product recovery. Modular architecture mainly contributes to diminishing the complexity of the product architecture by identifying physical chunks [14, 68]. As the modular architecture has a higher number of internal couplings within the module and less external couplings between modules, the modular product can be maintained or replaced effectively by substituting the modules [19, 64]. However, most of the modules in previous studies are generated based on the functional or physical relationships of the product architecture [65, 121, 122], and predefined as module variants by using optimization approaches [7, 90, 95, 122, 123], market-based decision making approaches [124] or data mining approaches [97]. Also, most of the previous modular product designs have focused more on clustering modules to maximize internal coupling and minimize external coupling without considering product recovery processes. Although the existing modules are well-defined and effective for manufacturing, these modules would not be easy to disassemble at the product recovery stage. If components with different materials and lifespans are mixed in a module, disassembly operators need to make more effort to fully disassemble the module into components or materials [34].

To develop modular architecture from the viewpoint of the product recovery, a novel design method is introduced to extend existing research from modular product design to eco-modular product design. The objective of this study is to determine eco-modular architecture and assess its degree of modularity by considering the product

recovery based on sustainable modular drivers. With the sustainable modular drivers, Markov Cluster Algorithm is applied to identify eco-modules, which is a chunk of components with similar materials and/or lifespans. Also, a novel modularity assessment method is proposed to quantify the degree of modularity of the eco-modular architecture by using module independence and module similarity metrics. The module independence metric indicates the degree of independence by assessing interface complexity between modules, while the module similarity metric indicates the degree of similarity within modules. Based on the results from the metrics, the eco-modular architecture can be selected.

5.2 A Process of an Eco-modular Architecture Design and Assessment Method

The proposed eco-modular architecture design method is shown in Figure 5.1. A design team developing a new product portfolio by considering product recovery would carry out the process outlined here. The process is similar in determining modular product architecture based on the basic physical interrelationships of each product in the product portfolio. However, the design team would include considerations of the product recovery process into its product architecture. In this study, eco-modular architecture is defined as a scheme by which the components with similar design features are organized into modules to enhance end-of-life characteristics of the architecture. The first step is to analyze current product architecture and product information. Designers can obtain the information on components' interaction based on the DSM, the types and number of interfaces, its complexity, material types, component lifespan, environmental impact, and so on from this initial step. In Step 2, sustainable modular drivers are identified and measured to cluster components into modules for product recovery. It is important to produce a feasible architecture design, so that physical connections between components are considered to develop eco-modular product architecture. The DSM from Step 1 and

the values of the sustainable modular drivers from Step 2 are converted to an adjacency matrix in Step 3. Based on the adjacency matrix, the Markov Cluster Algorithm is applied to identify eco-modular architectures while considering both the physical relationships between components and the sustainable modular drivers. The final step is to assess the modular architectures based on the module independence and similarity metrics. The module independence metric can measure interface complexity between modules to verify how complex the modular product is when disassembling modules at the EOL stage. The module similarity metric assesses the similarity of characteristics of the components in modules of a product. Finally, decision makers can select an eco-module architecture based on the assessment result.

Figure 5.1 The proposed process for eco-modular architecture design

5.3 Product architecture analysis

Product architecture can be defined as comprehensive representations of a set of characteristics, such as the number and type of components, the number and type of interfaces between components, and the fundamental structure of the product [26]. In order to emphasize design for recovery, the product architecture is explained with disassembly process as shown in Figure 5.2. A product is disassembled into components through modules which are sub-assemblies. The disassembly process incurs different amounts of disassembly process costs according to the difficulty of disassembly and the condition of modules after disassembly [34]. In the disassembly process of the architecture level, designers can collect information on the negative environmental impact, disassembly cost, product recovery cost, and reassembly cost. The product recovery and reassembly operations are then conducted to retrieve obsolete components. After disassembling the modules into components, the components can then be further disassembled into materials if a module contains components with different materials. The component based DSM is developed to represent interactions between components in a product. The component based DSM is used as a fundamental tool to represent interface complexity in Section 5.4.1 and develop adjacency matrices for the similarities of material or lifespan in Section 5.5.

Figure 5.2 An example of product architecture

5.4 Identification of sustainable modular drivers

Based on the product information, new modular drivers are required to be identified to configure modular architecture for the EOL stage. The modular drivers are used as different criteria to generate modules behind modularization [125]. Erixon [125] introduced 12 modular drivers to satisfy a company's strategic requirements: carryover, technology push, common unit, maintenance and recycling, to name a few.

In this study, sustainable modular drivers related to product architecture and sustainability are introduced to consider disassemblability for the product recovery as shown in Figure 5.3. An architecture factor is the interface complexity; this represents the complexity of functional and geometric connections between components. The interface complexity helps determine modules with high interface complexity between components to minimize interface complexity between the modules. The sustainability factors are component lifespan and materials. The sustainable factors are identified to cluster components with similar material or lifespan to form modules without disassembly at either the component or material levels. These sustainability modular drivers help reconstruct the modular architecture of commercial products into eco-modular architecture.

Figure 5.3 Three sustainable modular drivers

5.4.1 Interface complexity

As modular product design aims to maximize internal coupling within modules and minimize external coupling between modules [64], managing the ‘coupling’, which refers to the interface in this study, is important. The interface connects functions through material, energy, and signal flows among components via geometric contacts [126]. Thus, the interface plays a critical role in estimating the difficulty of disassembly as well as the functional importance between components and modules, quantitatively.

The author adopted interface types and weights that were introduced by Asikoglu and Simpson [71]. The interface types related to the physical connection are the attachment (A) and spatial (S), while the interface type related to functional interfaces are transfer (T), control and communication (C), field (F), and power (P) as shown in Table 5.1. The complexity of direct connections between components/modules is calculated by using the weighted-modular complexity score (wMCS) in equation (5.1) [71].

$$\begin{aligned} wMCS = & [w_i \times (\# \text{of } 1's \times 1)] + [w_i \times (\# \text{of } 2's \times 2)] + \\ & [w_i \times (\# \text{of } 3's \times 3)] + [w_i \times (\# \text{of } 4's \times 4)] + \\ & [w_i \times (\# \text{of } 5's \times 5)] + [w_i \times (\# \text{of } 6's \times 6)] \end{aligned} \quad (5.1)$$

Where, w_i is a weight of an interface type ($i = A, S, T, C, F, \text{ or } P$) as shown in Table 5.2. The weights (w_i) of different types of interfaces in Table 5.2 were determined based on the frequency of occurrence of interface types by using a non-linear weight function [71]. There are six levels of complexity according to combinations of interface types. The terms “# of 1’s, 2’s, 3’s, and etc.” are the number of interface complexity at each level, while the numbers 1 to 6 following these terms refer to the complexity constants at each level [78]. To calculate wMCS, the number of interfaces at each level is multiplied by the weights (w_i) and complexity constant.

Table 5.1 Definition of interface types [71]

Interface type	Definition
Attachment (A)	The structural connections between two components that require a type of connector (e.g. bolts, screws, rivets)
Spatial (S)	The geometrical and locational constraints of a component with respect to other components (e.g. snap-fit, welding)
Transfer (T)	The flow of materials or power between components (e.g. water flow in a coffee maker or in an iron)
Control & Communication (C)	The relationship of signal or information flow is communicated or controlled by another component. (e.g. circuit boards)
Field (F)	The interaction between two components in which one component can generate heat, vibration, or magnetic field
Power (P)	The electrical connection between two components unlike communications and controls interfaces

Table 5.2 Weight value of interface types [71]

Interface	Weight	Interface	Weight	Interface	Weight	Interface	Weight
A	2.974	SC	21.435	ATC	64.025	PCF	76.142
S	1.795	SF	22.843	ATF	66.137	TCP	75.598
P	6.832	SP	17.253	ATP	57.752	TFP	77.710
C	8.923	TC	36.735	ACF	64.568	ASTC	92.546
T	9.445	TF	38.143	ACP	56.184	ASTF	95.362
F	9.627	PF	32.916	AFP	58.296	ASTP	84.182
AS	9.538	CF	37.098	STC	60.488	ATCF	123.872
AT	24.838	PC	31.508	STF	62.600	ATCP	112.692
AC	23.793	AST	42.642	STP	54.215	ACFP	113.418
AF	25.201	ASC	41.074	SCF	61.032	ASTCF	163.815
AP	19.611	ASF	43.186	SCP	52.647	ASTCP	149.841
ST	22.480	ASP	34.801	SFP	54.759	ASTCFP	237.568

For example, in Figure 5.4 (a), the number ‘1’ in the cells of the DSM means that there are interconnections between two components. Based on the interconnections of the DSM in Figure 5.4 (a), the interface complexity is determined in the cells that have

the interconnections in Figure 5.4 (b). For example, when the interface type between components A and C are two screws (Type A) and one snap-fit (Type S), the value of the interface complexity is 7.743 ($=2.974 (A) \times 2 + 1.795 (S) \times 1$).

	A	B	C	D	E
A		1	1		
B	1		1		
C	1	1		1	
D			1		1
E				1	

(a)

	A	B	C	D	E
A		A	A(2),S		
B	A		AS		
C	A(2),S	AS		S	
D			S		A
E				A	

	A	B	C	D	E
A		2.974	7.743		
B	2.974		9.538		
C	7.743	9.538		1.795	
D			1.795		2.974
E				2.974	

(b)

Figure 5.4 An example of DSM with (a) physical relationship and (b) wMCS

5.4.2 Material

Environmental responsibility of manufacturers is extended beyond the manufacturing stage to customer usage stage and the EOL stage in the product lifecycle. Environmental regulations, such as the WEEE (Waste of Electrical and Electronic Equipment), EuP (Energy Using Product), and ELV (End-of-Life Vehicles), concerns fabrication and disposal of products [7]. Carefully selecting materials by considering the customer usage stage and the EOL stage is one of the most important considerations. From the consumer's point of view, certain materials can affect their health; from the manufacturer's perspective, the depletion of natural resources through overconsumption must be considered. Materials are selected in different ways to optimize production methods, function and structural demands, market or user demands, design, price, environmental impact, and lifetime [127]. To minimize environmental impact, products

at the EOL stage should be recycled and reused. Since modular architecture consists of modules that can be disassembled as a chunk, it can inherently improve disassemblability of the products. Accordingly, in terms of design for recycling, components with similar materials should be grouped in a module if components can be recycled by the same product recovery process. This will be advantageous in terms of reducing disassembly costs and recycling processes.

5.4.3 Lifespan

Lifespan is related to the residual value of an EOL product which is changing over time. When a product or a module is disposed of because of physical deterioration or technology obsolescence, the residual value is an indicator of whether or not the module can be performed for a second life. Therefore, the residual value of a product was estimated by its physical and functional lifetimes based on the empirical disposal data of the product in the market. The remaining lifetime (L_R) for the product recovery is represented with its mean lifetime (L_M) and actual lifetime (L_A) under the operation conditions as shown in equation (5.2) [128].

$$L_R = L_M - L_A \quad (5.2)$$

L_M is the component's total functional life and is estimated by the time-to-failure data for a family of components, while L_A depends on the actually used condition. The L_M of each component can be obtained by the empirical time-to-failure data and estimated by Weibull analysis [129]. The cumulative distribution function for the Weibull distribution is:

$$F(t; \beta, \eta) = 1 - \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (5.3)$$

Where, t is time to failure. The distribution is affected by two parameters: the scale parameter, η , and the shape parameter, β . The value of β is closely related to the

failure mode. When $\beta < 1$, there is infant mortality. $\beta = 1$ means that the failure rate is constant over the time (random failure). $\beta > 1$ indicates a high failure rate as time passes. The mean life L_M is measured by using the following equation [128]:

$$L_M = \eta \Gamma \left[\frac{\beta + 1}{\beta} \right] \quad (5.4)$$

In product recovery, the product lifespan can be an attribute for modular design. With a modular design method, components with similar or high lifespan can be grouped into a module. The components in the module can be treated by the same or similar reuse processes, so that a company can save recovery process costs.

5.5 Identifying eco-modules based on Markov Cluster Algorithm

After measuring and/or collecting the value of the sustainable modular drivers, the value is represented as an adjacency matrix to cluster components with similar material or lifespan into modules. Based on the adjacency matrix as an input, the eco-modular product architectures are configured by Markov Cluster Algorithm (MCL).

For clustering modules, there are three categories of most popular clustering techniques of data mining [130]; linear models, e.g., support vector machine; distance-based model, e.g., k-means clustering [9] and fuzzy c-means clustering [97]; hierarchical clustering [131]. However, the clustering techniques of the data mining group each data point, which is a component, into a module based on degree of distance between the components without considering their relationships. Accordingly, it has a high chance of generating unnatural modules that contain components with no relationships each other. Other clustering algorithms based on DSM are used to determine modules [15, 72, 79, 121]. Since DSM based clustering methods aim to maximize internal coupling within a module and minimize external coupling between modules for module identification, it can facilitate disassembly of modules from complete products. However, the DSM based clustering methods do not consider

disassembly within a module towards component and material levels to minimize opportunities for disassembly operation. Therefore, the methods are not suitable to develop eco-modular architecture based on the sustainable modular drivers. In order to overcome these issues and consider dependencies between components for developing eco-modules, the MCL which is one of graph clustering is applied. The MCL was developed by Van Dongen [132] and is a commonly used algorithm for clustering complex biological networks in the field of bioinformatics [133]. Characteristics of the MCL is remarkably robust to noise and missing information in data and is to extract more informative dataset than other alternative clustering methods for a network of pairwise interactions like Restricted Neighborhood Search Clustering, Molecular Complex Detection, and Super Paramagnetic Clustering [134, 135]. As this algorithm is simple, there is no high-level procedural instruction for assembling, joining, or splitting of groups [132]. The MCL can generate modules with high similarity values, and dismiss the connections between components that have low similarity based on the sustainable modular drivers. In this respect, the MCL is used to generate eco-modular architectures.

The clustering process by the MCL is explained in Figure 5.5. Intuition of graph clustering is to group nodes connected with high strength in one cluster. The MCL finds clusters in graphs by a mathematical bootstrapping procedure. The procedure is to compute random walks through the graph by using stochastic matrix (also called Markov matrix) that represents the mathematical concept of the random walks on the graph (<http://micans.org/mcl/>). The random walks in the MCL algorithm infrequently transit from node i in one cluster to another cluster to lead to node j in the same cluster [136]. The MCL is a fast and scalable unsupervised clustering algorithm based on simulation of stochastic flow in a graph.

Figure 5.5 Clustering process for identifying the eco-modules by the MCL

In the MCL, an adjacent matrix is developed with values of the sustainable modular drivers as weight value on the edges. The edges are identified by the physical relationships in the component based on the DSM. Then, the adjacent matrix is converted to a weighted undirected graph. Let $G=(V,E)$ be the undirected graph that includes self-loops; V denotes the node set and E means the edge set. A node in V is v_i , and an edge between v_i and v_j in E is represented as (v_i, v_j) . A weight value on the edge is denoted as $w(v_i, v_j)$, which represents the interface complexity, material similarity, or lifespan similarity. A is the adjacency matrix of a weighted and undirected graph as follows:

$$A(i, j) = \begin{cases} w(v_i, v_j) & \text{if } (v_i, v_j) \in E \\ 0 & \text{else} \end{cases} \quad (5.5)$$

When developing the adjacency matrix for material similarity, the material similarity is decided according to the experts' knowledge based on the material information, such as material property, conditioning process, recovery process, and so on. In this research, to simplify calculating the material similarity, the weight value of the material similarity is represented between 0 and 1. Equation (5.6) is an example of the weight value.

$$w(v_i, v_j) = \begin{cases} 1 & \text{if same material is used in } i\text{th and } j\text{th components} \\ 0.5 & \text{if similar materials are used} \\ 0.3 & \text{else} \end{cases} \quad (5.6)$$

For measurement of lifespan similarity between two components, the lifespan of components has to be predicted by designers based on the accumulated company data and knowledge. Then, the lifespan similarity between components is decided to build an adjacency matrix. Calculation of the lifespan similarity is represented by a ratio of the minimum lifespan and maximum lifespan between v_i and v_j in equation (5.7). If the lifespan is the same, the lifespan similarity would be 1. On the other hand, the lifespan similarity value would be close to 0. This means that one of the components has a short lifespan or there is a big difference in lifespans.

$$w(v_i, v_j) = \frac{\min \text{ lifespan}(v_i, v_j)}{\max \text{ lifespan}(v_i, v_j)} \quad (5.7)$$

When considering these modular drivers together, the weighted value of edges ($\bar{W}$) is calculated by the weighted average method as illustrated in equation (5.8).

$$\bar{W}(i, j) = \frac{w_1 \times \text{Interface complexity}(i, j) + w_2 \times \text{Material similarity}(i, j) + w_3 \times \text{Lifespan similarity}(i, j)}{w_1 + w_2 + w_3} \quad (5.8)$$

$$\sum_{i=1}^3 w_i = 1$$

Where, w_i is the weighted value of each sustainable modular driver.

After building the adjacent matrix, the adjacency matrix $A(i, j)$ should be transformed to Markov matrix, M , that is diagonally similar to a symmetric matrix. In order to identify random walks from the adjacency matrix, the sum of all outgoing edges, which is the sum of each column, equals to one as shown in equation (5.9). So, $M(i, j)$ represents the probability of transition of the random walks, which is termed as stochastic flow, from v_i to v_j [132].

$$M(i, j) = \frac{A(i, j)}{\sum_{k=1}^n A(k, j)} \quad (5.9)$$

The MCL process contains two operations: *expansion* and *inflation*. The expansion operation is normal matrix multiplication and represented as $M_{exp} = M \times M$. It allows the flow to connect different regions of the graph and becomes more homogenous. The expansion corresponds to random walks with many steps. It associates new probabilities with all pairs of nodes, where one node is the point of departure and the other is the destination. Higher length paths are more common within a cluster than between clusters.

$$M_{\text{inf}}(i, j) = \frac{M(i, j)^r}{\sum_{k=1}^n M(k, j)^r} \quad (5.10)$$

The inflation models the contraction of the flow in equation (5.10). It becomes thicker in regions of higher value on edges and thinner in regions of lower value on edges. The inflation operation has the effect to rescale each of the columns of M with the inflation parameter r . The parameter r is a non-negative real number. Each column j of a Markov matrix M is node j of the stochastic graph G . The inflation operation results in the stochastic matrix M_{inf} . The elements of the matrix M_{inf} correspond to the probability values on the edges. The inflation will boost the probabilities of intra-cluster and dismiss the probabilities of inter-cluster to result in cluster structures. Iterating expansion and inflation result in different clusters of the graph. Therefore, eco-modular architectures are generated based on adjacency matrix from each modular driver.

5.6 Assessment of modular architectures

After determining the eco-modular architectures, an assessment should be made of whether the architectures reflect the intent of the sustainable modular drivers or not. Since modular product architecture is composed of interfaces and modules, two modularity metrics are proposed to assess interfaces and modules: (1) module independence (MI) to assess interface complexity between modules; and (2) module similarity (MS) to analyze similarity within modules as shown in Figure 5.6. The MI is a ratio of interface complexity between modules to total interface complexity of a product in equation (5.11). The module similarity metric is the degree of similarity within modules in product architecture as shown in equation (5.12).

The following are assumptions to assess modular architectures with EOL strategies. (1) It is assumed that the MI metric represents the difficulty of disassembly. (2) It is assumed that the MS metric represents the possibility of disassembly. This is

because a module requires further disassembly at component or material level during product recovery process if modules have components with less similarity of lifespan or material. (3) It is assumed that the lifespan of a component is estimated by the Weibull analysis based on accumulated company data, and the lifespan of the component which is longer than a product lifespan can be performed well for its remaining life.

Figure 5.6 The assessment range of the proposed modularity metrics

MI has been modified from Newcomb, et al. [29]. The MI can be calculated by a ratio of intra-module interface complexity for all modules and total interface complexity in equation (5.11).

$$\text{Module independence (MI)} = \frac{\sum_{i=1}^N \text{Intra-module interface complexity}_i}{\text{Total interface complexity}} \quad (5.11)$$

The MI is calculated by using intra-module interface complexity instead of inter-module interface complexity because it yields that the MI is a maximum value when the interface complexity is low. Theoretically, the maximum value of MI is 1 if all connections are within modules but there are no connections between modules in a product. The minimum value of MI is 0 when the modules are a single component.

Since eco-modular product architectures were identified based on similar values, a designer has to assess the degree of similarity in each module. The MS is assessed by following equation (5.12).

$$\text{Module similarity (MS)} = \frac{\sum_{i=1}^N \text{Max}(S_{i,j})}{N} \quad (5.12)$$

$$S_{i,j} = \left[\frac{S_{i,1}}{n}, \frac{S_{i,2}}{n}, \dots, \frac{S_{i,j}}{n} \right], \quad \sum_{j=1}^n S_{i,j} = n \quad (5.13)$$

Where $S_{i,j}$ is the similarity ratio of j th different characteristics to the number of components in i th module (n), N is the number of modules in a product. For example, the first module consists of a component with a lifespan of 5 years ($s_{1,1}$), three components with a lifespan of 8 years ($s_{1,2}$), and two components with a lifespan of 10 years ($s_{1,3}$). In this case, the number of components in the first module is 6 ($n=6$), and $S_{1,j}=[1/6, 3/6, 2/6]$. As $S_{1,2}$ equals 0.5 which is the maximum value of the first module, it represents a lifespan similarity (S_l) of the first module based on equation (5.12) and (5.13). However, $S_{i,j}=0$ when all components have different lifespans. If all modules in a product consist of components with the same materials, $MS = 1$. Otherwise, it is 0 if each module has components with all different materials. Finally, to consider the MI and MS simultaneously, the modularity for the EOL stage (M_{EOL}) is developed by using the weighted average calculation as shown in equation (5.14). The modularity ranges from 0 to 1.

$$\text{Modularity for EOL stage (M}_{EOL}) = w_1 MI + w_2 MS_{Material} + w_3 MS_{Lifespan} \quad (5.14)$$

$$\sum_{i=1}^3 w_i = 1 \quad (5.15)$$

When M_{EOL} is close to 1, the modular architectures can be designed well with considerations of the product recovery. Accordingly, designers can choose an eco-modular architecture of which M_{EOL} is close to 1. As the M_{EOL} measures the modularity only for the EOL stage and is flexible, the M_{EOL} can be modified by adding other similarities that designers wish to measure. Figure 5.7 shows the proposed four regions with two thresholds (θ_1, θ_2) that indicate decision points for determining categories of a product architecture for EOL recovery options. The value of the thresholds can be decided by design strategies including customer demands for recovered products/modules, recovery cost and profit, and quality of recovered products/modules. The categorized architectures (g) can be represented as equation (5.16) based on the MI and MS, and provide a guideline for eco-modular architectures in the viewpoint of disassembly for product recovery.

$$g = \begin{cases} A, & \text{if } MS \geq \theta_1, MI \geq \theta_2 \\ B, & \text{if } MS \geq \theta_1, MI < \theta_2 \\ C, & \text{if } MS < \theta_1, MI \geq \theta_2 \\ D, & \text{if } MS < \theta_1, MI < \theta_2 \end{cases} \quad (5.16)$$

The four regions of product architecture are proposed based on the MI ($0 \leq MI \leq 1$) and the MS ($0 \leq MS \leq 1$): (A) eco-modular architecture, (B) eco-modules with high disassembly cost and time, (C) component reuse or recycle, and (D) disposal of a product as shown in Figure 5.7 (a). The eco-modular architecture in region A provides efficiency for product recovery process by minimizing the possibility of disassembly operations, and disassembly cost and time. In region B, the eco-modular architecture with high disassembly cost and time provides eco-modules but these connect with high interface complexity. These two eco-modular architectures can be processed for product recovery at the sub-assembly level in Figure 5.7 (b). However, when the module similarities are low because modules contain components with different lifespans and

materials as shown in region C, the modules have to be disassembled into components or materials. Then, components can be recycled or reused if interface complexity between modules is low. In region D, as both the module similarity and independence are low, the product can be disposed of.

(a) Four regions of modular product architecture

(b) Product recovery options of the modular product architecture in the four regions in product lifecycle

Figure 5.7 Modular architecture categories and their product recovery options in product lifecycle

To demonstrate the effectiveness of the proposed eco-modular design and assessment method, a case study is performed with a coffee maker in the next section.

5.7 Case study

In this section, the proposed design method is described in a case study of a coffee maker. The electric coffee maker is composed of a simple structure and mechanism but is still efficient. The specification of the coffee maker is described in Table 5.3. A functional diagram of the coffee maker is shown in Figure 5.8. The functional diagram represented energy, material, and signal flows between components [126].

Table 5.3 Specification of the coffee maker

#	Part name	Material	Weight(g)	Model (Philips HD7450)
1	Bottom cover	PP	80.5	<p>220V, 50Hz, 650W 4~6 cups / 0.6 L Brewing time < 10 minutes</p>
2	Silicon ring	Silicon	1.8	
3	Hot plate	Al	61.3	
4	Casing for heater	PP	55.2	
5	Heater	Al	118.2	
6	Power cord	Copper	120	
7	Water tube set	PP	14.7	
8	Silicon tube	Silicon	21.4	
9	Water reservoir	PP	243.2	
10	Steam sprout	PP	11.5	
11	Filter basket	PP	79.1	
12	Filter	PP	12.0	
13	Lid of coffee maker	PP	72.6	
14	Decanter	Glass	214.5	
15	Bottom casing	PP	155.0

Figure 5.8 Functional diagram of the coffee maker

5.7.1 Product architecture analysis

The physical relationships between components were identified after decomposing the coffee maker. The DSM was applied to represent interrelationships among components as shown in Figure 5.9. Accordingly, the DSM was used to develop an interface and adjacency matrix shown in Section 4.2. Modules were generated by the DSM clustering algorithm by Thebeau [121]. As shown in Figure 5.9, there are five modules: 1) bottom casing; 2) decanter and connecting parts; 3) water reservoir (upper casing) and water tube parts; 4) filter; and 5) heater.

Module No.		1st			2nd			3rd					4th		5th	
DSM		1	4	15	2	3	14	7	8	9	10	13	11	12	5	6
1	Bottom cover		1	1												
4	Casing for heater	1		1	1	1									1	
15	Bottom casing	1	1			1	1			1		1			1	1
2	Silicon ring		1			1										
3	Hot plate		1	1	1		1								1	
14	Decanter			1		1							1		1	
7	Water tube set								1							
8	Silicon tube							1		1	1				1	
9	Water reservoir			1					1		1	1	1			
10	Steam sprout								1	1		1	1			
13	Lid of coffee maker			1						1	1					
11	Filter basket						1			1	1			1		
12	Filter												1			
5	Heater		1	1		1	1		1							1
6	Power cord			1											1	

Figure 5.9 Modules of the coffee maker identified by DSM clustering algorithm

5.7.2 Identification of modular drivers for sustainable design

Interface design of the coffee maker was assessed based on equation (5.1) and the number of interface types and its weight values based on Table 5.2. As shown in Table 5.4, direct relationships between any two components were represented by the definition of the interface type. For example, Heater (No.5) and Silicon tube (No.8) are spatially

connected from Water reservoir to Heater, and from the Heater to the Steam sprout. So, ‘S(2)’ means that there are two spatial contacts. As the Heater and the Silicon tube transfer water in the coffee maker, it is also a ‘Transfer (T)’ interface type. The complexity of interface was developed as the adjacency matrix in Table 5.5.

Table 5.4 Interface matrix with interface types

	Interface	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Bottom cover				S											A(3),S
2	Silicon ring			S	S											
3	Hot plate		S		S	S,F									S,T	S
4	Casing for heater	S	S	S		S										S
5	Heater			S,F	S		P		S(2),T						F	S
6	Power cord					P										S
7	Water tube set								S(2),T(2)							
8	Silicon tube					S(2),T		S(2),T(2)		S,T	S,T					
9	Water reservoir								S,T		S(2)	S		S		A(3),S
10	Steam sprout								S,T	S(2)		T		S(2)		
11	Filter basket									S	T		S,T		S,T	
12	Filter											S,T				
13	Lid of coffee maker									S	S(2)					S(2)
14	Decanter			S,T		F						S,T				S
15	Bottom casing	A(3),S		S	S	S	S			A(3),S				S(2)	S	

Table 5.5 Adjacency matrix with interface values

	Interface	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Bottom cover				1.795											10.717
2	Silicon ring			1.795	1.795											
3	Hot plate		1.795		1.795	11.422									11.240	1.795
4	Casing for heater	1.795	1.795	1.795		1.795										1.795
5	Heater			11.422	1.795		6.832		13.035						9.627	1.795
6	Power cord					6.832										1.795
7	Water tube set								22.480							
8	Silicon tube					13.035		22.480		11.240	11.240					
9	Water reservoir								11.240		3.590	1.795		1.795		10.717
10	Steam sprout								11.240	3.590		9.445		3.590		
11	Filter basket								1.795	9.445			11.240		11.240	
12	Filter										11.240					
13	Lid of coffee maker								1.795	3.590						3.590
14	Decanter			11.240		9.627						11.240				1.795
15	Bottom casing	10.717		1.795	1.795	1.795	1.795			10.717				3.590	1.795	

To build the adjacency matrix for the clustering of modules, the information of each component was analyzed as shown in Table 5.6. The typical lifespan of the drip filter coffee machine was approximately 6 years and was approved by the European

Committee of Domestic Equipment Manufacturers and other stakeholders [137]. In the case of the product lifespan of components, as the coffee maker has a simple function and operating conditions, the lifespan of components would then only largely be affected by material types. Accordingly, an average lifespan of each component is assumed based on material types. The lifespan of components made of aluminum, copper, and glass was assumed as 10 years, and the lifespan of components made of PP or silicon was assumed as 8 or 5 years, respectively in Table 5.6.

Table 5.6 Material types and estimated lifespan of the coffee maker

#	Part name	Material	Typical product lifespan	Estimated component lifespan
1	Bottom cover	PP	6	8
2	Silicon ring	Silicon		5
3	Hot plate	Al		10
4	Casing for heater	PP		8
5	Heater	Al		10
6	Power cord	Copper		10
7	Water tube set	PP		8
8	Silicon tube	Silicon		5
9	Water reservoir	PP		8
10	Steam sprout	PP		8
11	Filter basket	PP		8
12	Filter	PP		8
13	Lid of coffee maker	PP		8
14	Decanter	Glass		10
15	Bottom casing	PP		8

Based on the product information, similarities of components were measured by equations (5.6) and (5.7). Similarity matrices which are the same as adjacency matrices were developed to represent material similarity and lifespan similarity as shown in Table 5.7.

In order to consider the product disassembly complexity (PDC) from Chapter 4 when developing alternatives of the eco-modular architecture, adjacency matrix with the PDC is developed in Table 5.8. A value of PDC for a single component is calculated based on equation (4.7) in Section 4.2.3 without considering the number of components and interfaces. Then, element values of the adjacency matrix are calculated by the sum of PDC values of two components that have interconnections. For example, a value of the element between bottom cover (1) and bottom casing (15) is 0.022 and it is

calculated by a sum of PDC value of the bottom cover, 0.011, and of the bottom casing, 0.011. Then, the range of PDC values in Table 5.8 is normalized to set the range between 0 and 1.

Table 5.7 Adjacency matrix for similarities of (a) material and (b) lifespan

(a)

Material similarity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Bottom cover				1.00											1.00
2 Silicon ring			0.30	0.50											
3 Hot plate		0.30		0.30	1.00									0.30	0.30
4 Casing for heater	1.00	0.50	0.30		0.30										1.00
5 Heater			1.00	0.30		0.50		0.30						0.30	0.30
6 Power cord					0.50										0.30
7 Water tube set								0.50							
8 Silicon tube					0.30		0.50		0.50	0.50					
9 Water reservoir								0.50		1.00	1.00		1.00		1.00
10 Steam sprout								0.50	1.00		1.00		1.00		
11 Filter basket									1.00	1.00		1.00		0.30	
12 Filter											1.00				
13 Lid of coffee maker									1.00	1.00					1.00
14 Decanter			0.30		0.30						0.30				0.30
15 Bottom casing	1.00		0.30	1.00	0.30	0.30			1.00				1.00	0.30	

(b)

Lifespan similarity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Bottom cover				1.00											1.00
2 Silicon ring			0.50	0.63											
3 Hot plate		0.50		0.80	1.00									1.00	0.80
4 Casing for heater	1.00	0.63	0.80		0.80										1.00
5 Heater			1.00	0.80		1.00		0.50						1.00	0.80
6 Power cord					1.00										0.80
7 Water tube set								0.63							
8 Silicon tube					0.50		0.63		0.63	0.63					
9 Water reservoir								0.63		1.00	1.00		1.00		1.00
10 Steam sprout								0.63	1.00		1.00		1.00		
11 Filter basket									1.00	1.00		1.00		0.80	
12 Filter											1.00				
13 Lid of coffee maker									1.00	1.00					1.00
14 Decanter			1.00		1.00						0.80				0.80
15 Bottom casing	1.00		0.80	1.00	0.80	0.80			1.00				1.00	0.80	

Table 5.8 Adjacency matrix for the product disassembly complexity

PDC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Bottom cover				0.021											0.022
2 Silicon ring			0.026	0.025											
3 Hot plate		0.026		0.021	0.022									0.021	0.022
4 Casing for heater	0.021	0.025	0.021		0.021										0.021
5 Heater			0.022	0.021		0.026		0.020						0.021	0.022
6 Power cord					0.026										0.027
7 Water tube set								0.020							
8 Silicon tube					0.020		0.020		0.021	0.019					
9 Water reservoir								0.021		0.021	0.021		0.023		0.022
10 Steam sprout								0.019	0.021		0.020		0.021		
11 Filter basket									0.021	0.020		0.019		0.020	
12 Filter											0.019				
13 Lid of coffee maker									0.023	0.021					0.023
14 Decanter			0.021		0.021						0.020				0.021
15 Bottom casing	0.022		0.022	0.021	0.022	0.027			0.022				0.023	0.021	

5.7.3 Identifying modules based on the Markov Cluster Algorithm

Based on adjacency matrices, the Markov matrix (M) was determined by equation (5.9) as shown in Table 5.9. Eco-modules were determined by using Markov Cluster Algorithm (MCL). Since the proposed method arranged constituents in modules while keeping the physical relationships, it could result in feasible eco-module architectures. In the case of the optimal number of modules, it was assumed that the number of modules for the coffee maker was decided as five modules to compare alternatives of eco-modular architectures. Accordingly, alternatives of eco-modular architectures were identified based on physical relationship, sustainable modular drivers, weighted average of these three modular drivers, and the product disassembly complexity from Chapter 4 by using MCL as shown in Table 5.10. The module number in Table 5.10 did not mean that the same number of modules for each architecture had the same characteristics, but showed that each architecture had five modules.

Table 5.9 Markov matrices for interface complexity, material similarity, and lifespan similarity

M _{Interface} =	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32
	0.00	0.00	0.06	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.50	0.00	0.20	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
	0.14	0.50	0.06	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
	0.00	0.00	0.41	0.20	0.00	0.79	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.28
	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.29	0.00	1.00	0.00	0.39	0.40	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.13	0.05	0.00	0.20	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.12	0.00	0.28	0.00	0.40	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.34	0.00	1.00	0.00	0.33
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.13	0.00	0.00	0.00	0.11
	0.00	0.00	0.40	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.05
	0.86	0.00	0.06	0.20	0.04	0.21	0.00	0.00	0.37	0.00	0.00	0.00	0.40	0.05
M _{Material} =	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19
	0.00	0.00	0.14	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.38	0.00	0.10	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.06
	0.50	0.63	0.14	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19
	0.00	0.00	0.45	0.10	0.00	0.63	0.00	0.17	0.00	0.00	0.00	0.00	0.25	0.06
	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.11	0.00	1.00	0.00	0.11	0.14	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.29	0.30	0.00	0.33	0.19
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.22	0.00	0.30	0.00	0.33	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.29	0.00	1.00	0.00	0.25
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.29	0.00	0.00	0.00	0.19
	0.00	0.00	0.14	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.06
	0.50	0.00	0.14	0.32	0.11	0.38	0.00	0.00	0.22	0.00	0.00	0.00	0.33	0.25
M _{Lifespan} =	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
	0.00	0.00	0.12	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.44	0.00	0.19	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.11
	0.50	0.56	0.20	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
	0.00	0.00	0.24	0.19	0.00	0.56	0.00	0.21	0.00	0.00	0.00	0.00	0.28	0.11
	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.10	0.00	1.00	0.00	0.14	0.17	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.28	0.26	0.00	0.33	0.14
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.22	0.00	0.26	0.00	0.33	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.28	0.00	1.00	0.00	0.22
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.28	0.00	0.00	0.00	0.14
	0.00	0.00	0.24	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.11
	0.50	0.00	0.20	0.24	0.16	0.44	0.00	0.00	0.22	0.00	0.00	0.00	0.33	0.22

Table 5.10 Clustering results based on MCL

Module No.	DSM clustering	MCL					
	Architecture (A) (based on physical relationship)	Architecture (B) (based on physical relationship)	Architecture (C) (based on interface complexity)	Architecture (D) (based on material similarity)	Architecture (E) (based on lifespan similarity)	Architecture (F) (based on weighted average)	Architecture (G) (based on the product disassembly complexity)
1	1	1	1	1	1	1	1
	4	2	4	2	2	2	2
	15	3	13	4	3	4	4
		4	15	15	4	13	5
		6			6	15	6
		14			15		13
		15					14
2							15
	2	5	2	3	5	3	3
	3		3	5	14	5	
	14		5	6		6	
3			6	14		14	
	7	7	7	7	7	7	7
	8	8	8	8	8	8	8
	9		9				
	10		10				
4							
	11	11	11	11	11	11	11
5	12	12	12	12	12	12	12
	5	9	14	9	9	9	9
	6	10		10	10	10	10
		13		13	13		

5.7.4 Assessment of modular architecture

The modularity for the EOL stage (M_{EOL}) was applied to assess each module and architecture. Additionally, the architecture (A) developed by DSM clustering algorithm in Table 5.10 was also assessed to determine the degree of modularity for product recovery.

From the results of the module independence assessment in Table 5.11, architectures (A) and (D) had the highest value with 0.54, while architecture (E) had the lowest value with 0.41. This means that architectures (A) and (D) contain low interface complexity between the modules. From the results of the material similarity assessment in Table 5.11, architecture (C) had the highest similarity with 0.85 because all modules contained components with a similar or the same materials, except for the second

module. In architecture (C) in Table 5.10, the second module inevitably contained components with different materials, such as the hot plate (3), heater (5), power cord (6), and decanter (14), to meet the functionality of the product. For results of the lifespan similarity assessment, architecture (C) was also the best architecture with the highest lifespan similarity value, 0.9; this was because almost all the modules contained components with a similar or same lifespan.

Table 5.11 Modularity assessment results

	MI	MS_material	MS_lifespan	M _{EOL}	MDL
Architecture A	0.54	0.56	0.89	0.66	13.56
Architecture B	0.43	0.69	0.69	0.60	25.12
Architecture C	0.53	0.85	0.90	0.76	24.45
Architecture D	0.54	0.65	0.75	0.64	21.78
Architecture E	0.41	0.50	0.70	0.54	23.12
Architecture F	0.53	0.66	0.76	0.65	24.45
Architecture G	0.44	0.70	0.70	0.61	29.78

Based on the individual results from the module independence, material similarity, and lifespan similarity, the results were represented on a scatter plot of categorized modular architectures in Figure 5.10. Two thresholds could be decided to identify four regions of the architectures according to design strategies of a company including customer demands for recovered products, recovery profit, and so on. In this case study, the two thresholds were assumed as $(\theta_1, \theta_2) = (0.7, 0.5)$. Region A contained architectures (A), (C), (D), and (F) with lifespan similarity. However, as the material similarity of these architectures was lower than θ_1 , except for architecture (C), these architectures had to be disassembled at the component level for recycling. Therefore, in this case study, architecture (C) would be the best architecture due to high module similarities within modules and high module independence between modules shown in Figure 5.10. Also, the M_{EOL} showed that architecture (C) was the best eco-modular architecture with the highest M_{EOL} value in Table 5.11. For architectures (B), (E), and

(G), the designer can plan to dispose of products because product recovery cost and time will be high. The proposed method was developed based on physical interrelationships in a product and resulted in the eco-modular architecture illustrated in the functional diagram of architecture (C) in Figure 5.11. Accordingly, architecture (C) will maintain its functions and enhance the product recovery process. Architecture (C) of this coffee maker could be recycled and reused without further disassembling the modules into components or materials. The characteristics of modules 1, 4, and 5 in architecture (C) could lead to reuse and recycle options because the modules consisted of components with the same material and lifespan. However, as modules 2 and 3 contained components with different materials and lifespans, these modules would have to be disassembled at the component or material levels for product recovery.

Figure 5.10 Categorized modular product architectures of the coffee maker in four regions according to the module independence and module similarity metrics

Figure 5.11 The eco-modular product architecture (C)

In order to compare a conventional method to the proposed assessment method, the minimum description length (MDL) was used to measure modularity by calculating the coupling complexity of the coffee maker [19] as follows:

$$MDL = \frac{1}{3} \left(n_c \log_2 n_n + \log_2 n_n \sum_{i=1}^{n_c} cl_i \right) + \frac{1}{3} S_1 + \frac{1}{3} S_2 \quad (5.17)$$

where, n_c is the number of modules; n_n is the number of components in DSM, and cl_i is the number of components in module i . S_1 is the number of empty cells in a module, while S_2 is the number of cells that have a link between modules. The lower the MDL, the better the modularity of a product. When calculating the MDL, values from the proposed modular drivers were not considered, but the number and size of modules and components were considered. By using the theoretic information, the author could identify well-established modules according to the ideal modularity concept that had high internal couplings within modules and low external couplings between modules. In terms of the result from the MDL calculation in Table 5.11, architecture (G)'s modularity was the worst architecture because it had the most number of empty cells in a module (S_1). Architecture (A)'s modularity was the best architecture. This was because architecture (A) had less empty cells within modules than other architectures. From the

results of Table 5.11, it could be seen that different viewpoints of modularity assessments resulted in different priorities of the architectures. With regard to the ideal modularity concept, architecture (A) had the best modules, while architecture (C) had good modularity for the EOL stage. It was difficult to compare the MDL and M_{EOL} because of the different purposes of the modularity. However, the M_{EOL} would be a good starting point to assess modularity for sustainable product design.

Additionally, after deciding the eco-modular product architecture, design improvement in a module level would be needed to produce various product variants including environmentally-friendly products. So, lifecycle assessment was applied to measure the environmental impact of the modules and to redesign the modules regarding material usage. Eco-Indicator 99 was used as the lifecycle assessment tool [138]. The Eco-Indicator 99 can measure three types of damage: 1) human health; 2) ecosystem quality (e.g. acidification); and 3) resources.

A scenario was assumed to enhance the product design to include product recovery. For the product recovery, material selection plays a key role in eco-product design because the materials not only can affect the health of consumers but also affect the depletion of natural resources through overconsumption. The material selection relies on expert knowledge in terms of material property, manufacturing process, and safety for users. In this case study, as almost all materials in the coffee maker were recyclable, it was assumed that heavy components of which weights are over 80 g, such as the bottom cover and bottom casing, heater, water reservoir, and decanter, were redesigned to reduce material usage by minimizing their size and thickness. Accordingly, the weight was reduced as shown in Table 5.12. As the result, the weight changes of the materials decreased the environmental impacts after re-design.

Table 5.12 Environmental impact changes after material reduction

Module No.	Part No.	Part name	Material	Weight (g)	EI (mPt)	Weight change (g)	EI change (mPt)
1	1	Bottom cover	PP	80.5	11.350	-10	-1.41
	4	Casing for heater	PP	55.2	7.783	0	0
	13	Lid of coffee maker	PP	72.6	10.237	0	0
	15	Bottom casing	PP	155.0	21.855	-25	-3.53
2	2	Silicon ring	Silicon	1.8	0.178	0	0
	3	Hot plate	Al	61.3	6.183	0	0
	5	Heater	Al	118.2	11.922	-18.2	-2.40
	6	Power cord	Copper	120.0	168.240	0	0
3	7	Water tube set	PP	14.7	2.073	0	0
	8	Silicon tube	Silicon	21.4	2.119	0	0
	9	Water reservoir	PP	243.2	34.291	-43.2	-6.09
	10	Steam sprout	PP	11.5	1.621	0	0
4	11	Filter basket	PP	79.1	11.153	0	0
	12	Filter	PP	12.0	1.692	0	0
5	14	Decanter	Glass	214.5	6.435	-14.5	-0.44
Sum				1261.0	294.080	-100.9	-13.87

5.8 Summary and Preview

In this chapter, a method is introduced to determine the eco-modular product architecture and its modularity assessment for product recovery processes. The proposed method contributes to facilitating the product recovery processes by recycling, reusing, and disposing of modules without further disassembly at the component or material levels. Also, the method helps designers quantify the degree of modularity of the eco-modular architecture from the viewpoint of the end-of-life stage. This study could show that current modular product design was extended to consider the product recovery processes which aim to restore the inherent value of retired products. Three sustainable modular drivers were proposed to consolidate components with high similarity and interface complexity into modules, aiming to recover the modules without further

disassembly at the component or material levels. Markov Cluster Algorithm was applied to identify alternative eco-modular architectures based on these the sustainable modular drivers. To check whether or not the eco-modular architectures reflect the intent of the sustainable modular drivers, a novel method has been developed to assess the degree of modularity from the viewpoint of product recovery. The degree of modularity supported the selection of the eco-modular architecture based on the module independence metric between modules and the module similarity metric. To demonstrate the usefulness of the proposed method, a case study with a coffee maker was performed.

The limitation of this proposed method is that it considers modular architecture for only a single product. More case studies need to be performed with different products to show the scalability and applicability of the proposed method. Also, the method will be extended to product family architecture design to improve the reusability of the eco-modules by sharing and exchanging the eco-modules in a product family.

This chapter illustrates a product architecture design for the end-of-life stage. To develop a sustainable product family based on the product architecture, a new concept of platform strategy should be developed with new criteria. Therefore, next chapter provides a method for determining sustainable platform with considering propagations of design changes, sustainability value, and commonality simultaneously.

Chapter 6. Sustainable Platform Identification for Product Family Design

To develop a sustainable product family, product architecture design and a platform strategy are necessary. For the product architecture, the degree of disassembly difficulty for a product is analyzed in Chapter 4 and the eco-modular product architecture is developed in Chapter 5. Then, this chapter introduces a method of determining a sustainable product platform for sustainable product family design as Step 4 in the SPFDM. Section 6.1 describes an overview of this chapter and Section 6.2 provides the process of the proposed method. In order to measure which components are sustainable, the author uses sustainability indicators that consist of environmental, economic, and social indicators. Then, as the value of each indicator is different and has different scope, a multi-attribute decision making approach is applied to aggregate the values into a single value, called a sustainability value in Section 6.3. Based on product information from Step 1 of the SPFDM, product dependency is analyzed to represent change propagation in Section 6.4. In Section 6.5, change propagation analysis is performed based on the product dependency and Bayesian network. The results of the change propagation analysis are represented as a risk in redesigning each component that is calculated based on conditional probability from Bayesian network and redesign cost. In order to decide a sustainable platform based on information from previous sections, Fuzzy Inference System is applied in Section 6.6. A case study is carried out to evaluate the proposed method in Section 6.7 and summary of this chapter is represented in Section 6.8.

6.1 Overview of a Platform Strategy

Governments and international agencies have designed not only domestic regulations but also international regulations encouraging designers and manufacturers to take

stronger environmental stewardship [6]. Also, manufacturers endeavor to meet legislative requirements for the environment while making profits by selling sustainable products. The sustainable products are defined as products that aim to be more environmentally friendly and profitable with enhancing social benefits during product lifecycle [8]. Also, sustainable product design considers longer product life cycle whilst competing alongside existing products [139].

However, existing studies of product design have less considered sustainability aspects, such as, environmental, economic, and social aspects. Eco-design has been researched to consider mainly environmental impact for product design [1, 42, 107]. The environmental impact is measured by the life cycle assessment (LCA) and then a single product with lower environmental impact is selected as eco-design. The eco-design method has focused on material types and manufacturing processes of components for designing the single product more sustainable over product lifecycle rather than considering product architecture enhancement and product family design [42, 140]. Otherwise, a product family design has focused on maximizing profits to satisfy a variety of market segments effectively without considering environmental performance [32]. The product family consists of common, variant, and unique modules. The common modules are shared in all products in a family; the variant modules are shared in two or more products that differ in one or more aspects; the unique modules are used to differentiate a variant from other products in a product family. Accordingly, identifying a platform in product family design is important to enhance a variety of products and control sustainability of the product family effectively.

Product redesign towards sustainable product and next generation of products is inevitable. In this sense, risks in redesigning components have to be critically considered when deciding the platform. If current platform design has to be redesigned towards a sustainable product, the design change of the platform can be propagated other components and products in a product family because the platform is intricately interwoven with the constituents in the product family. When the platform generates

high environmental impact along the lifecycle, this negative impact will affect entire products in the product family as well.

Therefore, a novel method is necessary to address a new concept of a sustainable platform by considering sustainability values and risks in redesigning products in terms of design modification in the family. The objective of this chapter is to identify the sustainable platform by extending the conventional platform concept identification into the sustainable platform concept.

6.2 A Method for Sustainable Platform Identification

The overview of the proposed method is shown in Figure 6.1. In phase 1, measurable sustainability indicators are selected according to government legislation and/or a company strategy to directly use data of the indicators. The indicators and corresponding values can be collected from historical data related to sustainability in companies. Then, a multi-attribute decision making approach is applied to aggregate and rank the values of the indicators. In phase 2, constituents of products are analyzed and listed in bill of materials with raw materials, sub-assemblies, components, and its quantities, to name a few. This phase is to collect products' information, and analyze dependency between components and product architecture. Phase 3 is to analyze the change propagation for product redesign based on the dependency from Phase 2. Bayesian network is utilized to determine the likelihood of each component based on their dependency and then predict components to be redesigned. Risk values are calculated by the product of the likelihood and redesign cost. In the final phase, a sustainable platform and components' characteristics are identified by using a fuzzy inference system for decision making based on information on sustainability values from phase 1, risk value from phases 2 and 3, and commonality.

Figure 6.1 Overview of the proposed methodology for a sustainable platform identification

6.3 Phase 1: Aggregation of Indicator Data to Sustainability Value

6.3.1 Types of Sustainability Indicators

The most eco-design tools have focused on measuring environmental impact for considering sustainability. However, to make sustainability accessible in product design, sustainability indicators are needed by integrating environmental compatibility, economic requirements, and social aspects of a product [141]. Accordingly, the sustainability indicators are categorized in three aspects as follows.

(1) Environmental sustainability and indicator

Environmental sustainability is for protecting natural environments. One of the biggest issues is the generation of greenhouse gas (GHG) during product life cycle. The GHG is “gaseous constituent of the atmosphere that absorbs and emits radiation at

specific wavelengths within the spectrum of infrared radiation” [142]. The most abundant GHG is carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and chlorofluorocarbons (CFCs). As these GHGs that cause the greenhouse effect and global warming are strongly related to the environment, previous literature mainly considers GHG, especially, CO₂ emission, and recycling issues as an environmental indicator [50, 143-145].

In order to assess environmental impact over the product lifecycle, a model for the i th component’s environmental impact (E_i) is proposed as a function of material’s mass and environmental factors as followings:

$$E_i = E_i^{mat}(m_i) + E_i^{pro}(m_i) + E_i^{tran}(m_i) + E_i^{use}(m_i) + E_i^{eol}(m_i) \quad (6.1)$$

Where, m is material mass; E_i^{mat} , E_i^{pro} , E_i^{tran} , E_i^{use} and E_i^{eol} are weighted factors for the environmental impact over the product lifecycle that consists of material extraction (mat), production (pro), transportation ($tran$), use (use), and end-of-life (eol) stages. This is because each stage causes a different amount of the environmental impact. These weighted factors are from inventory data like environmental priority strategy [146], Ecoinvent LCA database [147], and eco-indicator 99 [148]. As the equation (6.1) can be a baseline, designers can add terms related to their strategies and modify the equation (6.1) to reflect the real situation of companies.

Examples of possible indicators for environment aspects are listed in Table 6.1 based on ISO and NIST regulations. ISO 14031 is to guide organizations to understand and evaluate environmental performance [149]. National Institute of Standards and Technology (NIST) designed sustainable manufacturing indicator repository and recommended it to manufacturing companies that are interested in measuring sustainability performance [150].

Table 6.1 Examples of environmental indicator

Reference	Category	Environment indicator
ISO 14031 for organization [149, p. 11]	Environmental condition indicator (ECI)	Groundwater level Rate of replenishment
	Environmental performance indicator (EPI)	$EPI = OPI + MPI$
	Operational performance indicator (OPI)	Quantity of water used per day Quantity of water used per unit of production
	Management performance indicator (MPI)	Amount of money spent on research into methods for reduction of water consumption
NIST sustainable manufacturing indicators [150]	Emission	Fluid emission, Gaseous emission, Solid waste emission, and Waste energy emission
	Resource consumption	Water use, Virgin material use, Energy use, and Packaging material use
	Pollution	Hazardous substances, Greenhouse gases, Ozone-depleting gases, and Other harms to environment
	Natural habitat conservation	Biodiversity, Habitat management, and Conservation

(2) Economic sustainability and indicator

Economic sustainability is closely related to costs over product life cycle. As the customer intention to purchase the products is affected by a market cost, sustainable products have to keep affordable prices by reducing costs in a system related to material use, transportation, and energy use [50, 143, 151]. Therefore, economic indicators are needed to analyze and compare costs of the products.

In Table 6.2, there are examples of economic indicators in three different systems. For a bioenergy system, Dale, et al. [152] proposed criteria for choosing socioeconomic indicators, and recommended socioeconomic indicators for sustainability of biofuels. For sustainable manufacturing, NIST indicators [150] were classified into three items like profit, cost, and investment for measuring economic performance. For a renewable

energy system, Liu, et al. [151] chose net present cost, cost of energy, return on investment, and energy generation as economic indicators.

Table 6.2 Examples of economic indicator

Reference	Category	Economic indicator
Dale, et al. [152] for bioenergy system	Energy security	Energy security premium
	External trade	Fuel price volatility, Terms of trade, Trade volume
	Profitability	Return on investment, Net present value
	Resource conservation	Depletion of non-renewable energy resources, Fossil energy, Return on investment
NIST indicators for sustainable manufacturing [150]	Profit	Profit earned by organization
	Cost	Material cost, Production cost, Transportation cost, End-of-service-life product handling cost
	Investment	General investment, Eco-friendly investment
Liu, et al. [151] for renewable energy system	Economic aspect	Net present cost, Cost of energy, Return on investment, Energy generation

In this chapter, the lifecycle cost (LCC) of a product family is considered as economic indicators. The calculation of the LCC is to measure costs from five stages of product lifecycle. The LCC for i th component (LCC_i) consists of material cost (C_i^{mat}), production cost (C_i^{pro}), transportation cost (C_i^{trans}), use (service) cost (C_i^{use}), and end-of-life cost (C_i^{eol}) in equation (6.2).

$$LCC_i = (C_i^{mat} + C_i^{pro} + C_i^{trans} + C_i^{use} + C_i^{eol}) \quad (6.2)$$

$$C_i^{mat} = \alpha_i^{mat} N_i m_i \quad (6.3)$$

$$C_i^{pro} = \alpha_i^{pro} N_i \quad (6.4)$$

$$C_i^{trans} = \alpha_i^{trans} N_i \quad (6.5)$$

$$C_i^{use} = (\alpha_i^{use} + C_i^{disassy} + C_i^{assy}) f_i \quad (6.6)$$

$$C_i^{eol} = \alpha_i^{disposal} n_i - \beta_i^{recovery} (N_i - n_i) + C_i^{disassy} \quad (6.7)$$

Where, α_i is unit cost of each stage. C_i^{mat} represents material cost for producing i th component, and is calculated by multiplying unit cost of material for i th component (α_i^{mat}), the number of i th component in a product (N_i), and material weight of i th component (m_i) in equation (6.3). C_i^{pro} and C_i^{trans} are calculated by a product of unit cost of each stage and N_i as shown in equations (6.4) and (6.5), respectively. C_i^{use} in equation (6.6) is the service cost for disassembling failed components and installing new components [18]. Accordingly, it includes disassembly and assembly costs for the service process. f_i is the service frequency of the i th component. C_i^{eol} is the end-of-life (EOL) cost. The EOL stage has three main options: reuse, recycle, and disposal. The reuse and recycle options can generate returns, while the disposal option can incur costs. In this sense, C_i^{eol} is modelled as equation (6.7) with the number of disposed components (n_i), the number of components for reuse or recycle ($N_i - n_i$), returns from the reuse and recycle options ($\beta_i^{recovery}$), and disassembly cost. Therefore, EOL stage aims to reduce the LCC by reusing components and recycling materials of the components. After calculating LCC for i th component, the LCC of k th product that has I components is calculated as following:

$$LCC_k = \sum_{i=1}^I (C_i^{mat} + C_i^{pro} + C_i^{trans} + C_i^{use} + C_i^{eol}) \quad (6.8)$$

(3) Social sustainability and indicator

Since social sustainability reflects custom, culture, and customer's satisfaction, the social impact varies in different localities. Accordingly, as it is hard to define which

indicators are closely related to the social sustainability, most previous literature mentions social impact weakly. Generally, the social sustainability is related to how the system benefits customers and has an effect on the regional characteristics like economic, cultural, and social condition. Accordingly, the social indicators were selected, such as the health, well-being, safety, and customer satisfaction [50, 143]. Furthermore, possible indicators for social aspects were chosen according to the priority of their research field. Linke, et al. [153] chose factors related to employee's physical condition, education, and safe working environment in grinding industry as the social indicator. These factors included *human rights training for security personnel, recordable injury rate, blood lead level, and safety*. The extended social indicator was proposed as productivity that is the ratio of labors actual working hours to their scheduled working hours. Liu, et al. [151] considered *households benefited and new jobs created* as social indicators in a renewable energy system. These factors are the benefit of the system to the near community. NIST [150] focused on employee, customer, and community well-being indicators for manufacturing products. The employee indicator contains health and safety, development, and satisfaction. The customer indicator is to measure health and safety, satisfaction, and customer rights. The community indicator is for quantification of community well-being such as human rights, justice, and population.

Considering all performances for developing a sustainable product would be ambitious to rigorously validate results with two main reasons. First, since the definition of sustainability is not clear in the field of product design, there are not clear rules to select sustainable indicators under three aspects: economic, environmental, and social performances. Accordingly, to select the indicators for each aspect is challenging and depends on case by case. In previous works, although researchers have assessed the sustainability of products or systems quantitatively, and compared it each other, they have used different indicators under the same aspect or the same indicators under different aspects. For example, researcher A used air quality of the working environment

as an environmental indicator, while researcher B used the air quality of the working environment as a social indicator. Second, selection and quantification of social indicators are difficult. Although environmental and economic aspects can be quantified by proper methods and tools, combining all aspects into product design is difficult because social indicators are difficult to quantify. Since social sustainability reflects custom, culture, and customer's satisfaction, the social aspect varies in different localities, so that most previous literature mention social impact weakly. Therefore, decision-makers have selected the most appropriate indicators and modify the existing indicators to measure what they want to know for sustainable design.

6.3.2 A Multi-Attribute Decision Making Approach for Comparison of Sustainability Values between Products in a Family

Each indicator reflects sustainability issues, but the measured multiple indicators are frequently in conflict with their different goals. Therefore, a multiple attribute decision making (MADM) approach is utilized to aggregate indicators' values for selecting the best sustainable product. There are several MADM approaches, such as Analytical Hierarchy Process (AHP) [154], Data Envelopment Analysis (DEA) [155], Grey Relational Analysis (GRA), Simple Additive Weighting (SAW) [156], The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), combination of fuzzy theory, and so on [157, 158]. Overall, these decision making approaches are able to apply in this study. However, some approaches like AHP and TOPSIS uses subjective scales with expert knowledge to rank attributes. The values of indicators cannot be used directly in these methods. DEA requires multiple inputs and outputs that sustainable indicators in this study are not able to support, to build linear programming [159]. SAW should be used only when attributes have identical units, so that normalization of the attributes with different units is necessary for this study.

Grey relational analysis (GRA) is one of MADM approaches, which is used to measure the degree of similarities between multiple indicators under incompleteness information [151, 157, 160]. The purpose of using GRA is to simplify original MADM problems to a single attribute decision making problem. There are three reasons why GRA is implemented in this research. First, although sustainability indicators are under the same sustainability category, the indicators have different target values according to their conditions like lower-the-better condition or higher-the-better condition. GRA can deal with this issue by measuring distance between real data and target values. Second, each indicator under the same sustainability category has different dimensions and scope. GRA contains normalization process, called as grey relational generating, in order to translate the values of the indicators into comparability sequence. Third, usually, indicators contain complete and incomplete information [151]. The complete information is only that the values of each indicator are directly from real history data of a company, and that designers have target values of the indicators between 0 and 1, e.g., lower GHG gas indicator value is (target value is 0 here), the better sustainability indicator value is (target value is 1). Except for the information, nothing is clear between the indicators. GRA has a merit of global comparison between comparability sequence which is a data set of indicators, and reference sequence which is a data set of target values against the indicators' value instead of local comparison by measuring the distance between two points [140]. Thus, it can not only deal with this issue but also avoid the side effect of subjective setting of parameters within the model [140]. Therefore, the GRA can be a proper method to solve a MCDM problem.

To aggregate and then rank values of indicators by using GRA, the collected raw data of sustainability indicators from Phase 1 are represented as y_{ij} which accounts for a value of j th attribute (indicator) under i th alternative (component) as shown in matrix Y in equation (6.9). Through equation (6.10) for the larger-the-better attribute, equation (6.11) for smaller-the-better attribute, and equation (6.12) for the-closer-to-the-desired-

value- y_j^* -the-better, the matrix Y is normalized to the comparability sequence in matrix X . Then, all element values in the comparability sequence of the matrix X are scaled into $[0, 1]$.

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1j} & \cdots & y_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ y_{i1} & \cdots & y_{ij} & \cdots & y_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ y_{m1} & \cdots & y_{mj} & \cdots & y_{mn} \end{bmatrix}, \quad X = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \quad (6.9)$$

$$x_{ij} = \frac{y_{ij} - \text{Min}\{y_{ij}, i = 1, 2, \dots, m\}}{\text{Max}\{y_{ij}, i = 1, 2, \dots, m\} - \text{Min}\{y_{ij}, i = 1, 2, \dots, m\}} \quad (6.10)$$

for $i=1, 2, \dots, m$ $j=1, 2, \dots, n$

$$x_{ij} = \frac{\text{Max}\{y_{ij}, i = 1, 2, \dots, m\} - y_{ij}}{\text{Max}\{y_{ij}, i = 1, 2, \dots, m\} - \text{Min}\{y_{ij}, i = 1, 2, \dots, m\}} \quad (6.11)$$

for $i=1, 2, \dots, m$ $j=1, 2, \dots, n$

$$x_{ij} = 1 - \frac{|y_{ij} - y_{ij}^*|}{\text{Max}\{\text{Max}\{y_{ij}, i = 1, 2, \dots, m\} - y_{ij}^*, y_{ij}^* - \text{Min}\{y_{ij}, i = 1, 2, \dots, m\}\}} \quad (6.12)$$

for $i=1, 2, \dots, m$ $j=1, 2, \dots, n$

When converting various indicators into a total sustainability indicator, grey relational coefficient, $\gamma(x_{0j}, x_{ij})$, is calculated to measure the degree of absolute distance between comparability and reference values by using equation (6.13).

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{ij} + \zeta \Delta_{\max}} \quad (6.13)$$

Where,

$$\Delta_{ij} = |x_{0j} - x_{ij}|$$

$$\Delta_{\min} = \text{Min}\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

$$\Delta_{\max} = \text{Max}\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

$$\zeta \in [0, 1]$$

Where, Δ_{ij} is the absolute distance between comparability sequence (x_{ij}) and reference sequence (x_{0j}). The distinguishing coefficient, ζ , ranges from 0 to 1 and is usually adopted as 0.5 [151, 157, 161]. Consequently, the values of the sustainability indicators can be graded and then compared by grey relational grade, $\Gamma(X_0, X_i)$, as shown in equation (6.14).

$$\Gamma(X_0, X_i) = \sum_{j=1}^n w_j \gamma(x_{0j}, x_{ij})$$

$$\sum_{j=1}^n w_j = 1$$
(6.14)

Where, w_j is the weight value of j th indicator. All the summation of weights in i th component should be 1.

In order to apply weight values to the three categories of the sustainability indicators, the grey relational grade is broken down into three categories: environmental (E), economic (C), and social (S) categories. Consequently, the total sustainability value of a product (δ) is calculated by equation (6.15).

$$\delta = \sum_{i=1}^m (\alpha_i E_i + \beta_i C_i + \gamma_i S_i)$$
(6.15)

The total sustainability value includes the weight values, α_i for the E , β_i for the C , and γ_i for the S . The weight values can be developed based on decision makers in companies according to a company strategy, accumulated design knowledge, and designers' preference. The total sustainability value itself is a quantitative index, so that the designers can determine the degree of sustainability for components and products.

6.4 Phase 2 Product Dependency Analysis

To understand product architecture and its dependencies, information on products in a family are collected like the component lists, material types, manufacturing process, weight, and components' relationships. Based on the information, the product architecture and dependencies can be described by matrix-based approaches. There are four types of matrix according to scope of domain in the matrix based approaches: (a) intra-domain matrix for representing relationships between elements in the same domain, e.g., design structure matrix, (b) inter-domain matrix for mapping two different domains, as known as domain mapping matrix, (c) combined application of intra- and inter-domain matrices, e.g., quality function deployment, (d) multiple domain matrices [162].

In this phase, dependencies between components in a product are important to understand product architecture that is an arrangement of component interacting each other to perform desired functions. Since this research focuses on the dependencies between components in a product, the scope of the domain for matrix-based approaches is considered as intra-domain. Therefore, design structure matrix (DSM) is used to model product architecture, which is represented as the intra-domain matrix. DSM has become widely used in product design with different names as known as dependency structure matrix, dependency map, interaction matrix, incidence matrix, precedence matrix, and problem-solving matrix [163]. DSM provides a clear representation of the product architecture, and supports clustering components to determine modular architectures [15, 19, 68, 87, 164, 165]. Furthermore, the interdependencies of DSM can be extended to predict change propagation in a product during product redesign [85, 88, 166]. For example, if a design change starts from component *a* in Figure 6.2, components *b*, *c*, *d*, and *f* would be affected because of interconnection with the component *a*. As these affected components have other connections physically with other components, the affected design change of the component *b* propagates to the component *d*. To define directional nature, a component is distinguished to both direct

dependency, which belongs to the column of the source of the change in DSM, and indirect dependency, which is affected by components under the direct dependency, in Figure 6.2 [88].

Based on the dependency relationships in the DSM, the change propagation is modelled by Bayesian network in order to represent a tendency of the change propagation to change the conditional probability of components in next section.

Figure 6.2 Direct and indirect dependencies of component *a* in design structure matrix

6.5 Phase 3 Identification of Product Redesign Opportunities

As each component in a product is intricately interwoven each other, it is needed to consider direct and indirect dependencies and its impact for product redesign. A design change to a component may propagate and result in significant impacts to other systems. Therefore, the change propagation should be considered to identify product redesign opportunity for sustainable platform design. The change propagation mechanism can be modelled by the risk measurement based on the change prediction method from Clarkson, et al. [88], and Hu and Cardin [167]. In this study, the risk is defined as the potential redesign cost according to the particular design change in a product of a

product family. The risk aims to estimate how much manufacturers will cost while redesigning current product towards sustainable products. The cost of product redesign relies strongly on the required particular design changes [88]. In this sense, the risk value is calculated by a product of redesign costs and likelihood.

The redesign cost is the costs of components or system elements that are required during redesigning a product. As reducing the redesign cost is an important issue of companies, the redesign costs are considered. Also, in order to predict the change propagation during product redesign, it is critical to model dependencies between components and the change propagation. There are two possible methods for modelling the change propagation with conditional probability for this research: an influence diagram and a Bayesian network [168]. The Bayesian network is a probabilistic graphical model that represents a set of random variables and their joint probability. Since the Bayesian network is a directed acyclic graph, it can represent direct dependency which is a fundamental principle of change propagation as mentioned in the previous phase. It makes the Bayesian network suitable for forecasting, data mining, risk assessment, and other real world applications [169]. However, the Bayesian network can deal with continuous variables in only limited manner and cannot be used to model the correlation relationship between random variables that contains feedback loops [170]. The influence diagram can be developed based on the Bayesian network by adding decision and utility nodes as well as functional arc with utility function and information arc [171]. Since the influence diagram aims to identify decision options that have the highest expected utility [172], it contains redundant information and produces a complicated model to represent product redesign opportunities for this study. Hence, Bayesian network is utilized to represent the likelihood of a potential design change of components and the dependencies for updating probability distribution of components when particular changes occur. In this study, the definition of likelihood is a conditional probability to predict how components are affected and how a design change is propagated in complex product architecture. Bayesian network can be represented as

direct acyclic graphs in which nodes are components and edges are direct dependencies between components. Each node has two states: *redesigned* state and *stable* state.

Product redesign towards sustainable design can be processed at planning stage for considering a product platform and new technologies; at concept development stage for investigating feasible design concepts; at system-level design stage for developing product architecture, components, and modules; and at detail design stage for defining component geometry and material among the product development process [14]. In this research, these processes are represented as early product design stage. However, in order to model Bayesian network in the early product design stage, it is difficult to analyze conditional probability of entire constituents of a product because the number of parameter in the conditional probability table (CPT) grows exponentially according to an increase in the number of parent nodes [173]. For example, if component A (a child node) is affected by 10 components (parent nodes), designers should fill in the CPT of the component A with size 2^{10} cells for binary variables. To overcome this difficulty, noisy-OR model is used to reduce logarithmically the number of parameter in the CPT. Noisy-OR model is an approximation technique for modeling disjunctive interactions between causes (parent nodes). The model assumed that all parent nodes can be sufficient to cause child (effect) and their ability to influence the child are independent of the presence of other parent nodes [173, 174]. For example, if all variables have two states like ‘True’ and ‘False’ and a variable V has 3 parents, a CPT for the V has $2^3 = 8$ probability distributions. However, this assumption would ignore any synergy between causes in accordance with combined impact of the causes on the effect variable [172]. When using noisy-OR model, three noisy-OR distributions are required for developing the CPT and then other five probability distributions can be estimated based on the noisy-OR distributions. A detailed example for this is explained in Section 6.7.3. Accordingly, when designers analyze a complex system like a car for developing a CPT, the noisy-OR model will offer a significant advantage because the fewer parameters are required for the noisy-OR model. Suppose each cause B_j which is the parent node can

produce effect E_i which is child node with probability f_{ij} . The effect of all parents with direct and indirect dependencies can be represented as following:

$$\begin{aligned}
 P(E_i | par(E_i)) &= P(E_i | B_1, \dots, B_n) \\
 &= 1 - \prod_j (1 - P(E_i | B_j)) \\
 &= 1 - \prod_j (1 - f_{ij})
 \end{aligned} \tag{6.16}$$

Finally, the risk value is measured by a product of likelihood and redesign cost as followings:

$$R_i = P(E_i | B_1, B_2, \dots, B_n) \times C_i^{redesign} \tag{6.17}$$

Where, R_i is a risk value of i th component; $P(E_i | B_1, B_2, \dots, B_n)$ is the likelihood which is the conditional probability of i th component linked to causes B ; $C_i^{redesign}$ is the redesign cost of i th component. Under dynamic market condition and uncertainty, as designers may have difficulty to predict the change propagation, the risk value helps designers identify which components have high possibility to be redesigned. Since designers and companies would have lots of accumulated design knowledge and historical design data for product design, the designers can define and estimate the likelihood and redesign cost [167]. For the likelihood, it can be determined by expert elicitation analysis that helps evaluate subjective probability judgment [175]. In this research, since product redesign carried out at the early product design stage before acquiring the likelihood and redesign cost, the estimation of the likelihood and redesign cost would not limit the scope of design practice. Furthermore, the unknown likelihood and redesign cost of new concepts and variations of a product would be estimated based on the design knowledge and historical design data.

6.6 Phase 4 Identification of a Sustainable Platform

A platform for the current product family design is selected to maximize commonality and minimize production costs and lead time. However, as a modification of platform design can affect entire products in a family, dependency relationships in product architecture have to be applied to identify a sustainable platform rather than considering the only commonality. Therefore, in this study, a platform strategy is extended to a sustainable platform by considering not only economic performance but also environmental performance, social performance, and risk in redesigning a product. The sustainable platform has three characteristics: (a) low risk to design change of linked components, (b) high sustainability value, and (c) common modules or components in a product family. These characteristics are criteria for identifying the sustainable platform. The risk is used to estimate the robustness of components under product redesign condition. The sustainability value is considered to determine sustainable components in the product family. The commonality value of the product family is calculated by the following equation from [97].

$$\theta_i = \frac{\sum_{p=1}^P q_{i,p}}{P} \quad (6.18)$$

Where p is the number of products ($p = 1, 2, \dots, P$). $q_{i,p}$ is a quantity function and is equal to 1 if product p uses component i , otherwise, 0. If $\theta_i = 1$, i th component is used in all products in the product family. Otherwise, θ_i represents a proportion of the number of components used in the product family. Consequently, components that satisfy these characteristics can be selected as the sustainable platform for sustainable product family design.

Identifying a sustainable platform can be considered as classification problem to identify which components with sustainability value, risk value, and commonality

belong to which characteristics of components. The classification can be implemented in mathematical formulae and machine learning methods that include rule-based models like association rule mining [97] and decision trees such as C4.5 [176]. Since classification methods in machine learning like C4.5 are considered as an instance of supervised learning, the labeled training data is necessary to infer a function. The information on this study cannot provide the expected output for training data. When applying clustering methods under unsupervised learning like k-mean clustering on this phase, the characteristics of components would be modified to interpret each cluster. For applying other methods to this study, specific information and effort are required with respect to the characteristics of the methods.

In this study, the fuzzy inference system (FIS) is applied to identify a sustainable platform because problem characteristics are as followings: (1) Although crisp inputs for identifying a sustainable platform are determined from previous phases, the range or membership of the inputs are not clearly defined according to a number of different fuzzy linguistic sets, (2) There are no acceptable mathematical models to describe relationships between inputs and outputs, (3) Decision rules from experts can be generated to solve problems and support decision-making under uncertainty. Under the problem characteristics, the FIS should be a useful method [177]. The FIS contains fuzzy if-then rules expressed fuzzy antecedents and consequents to represent expert knowledge [178]. Therefore, the FIS is utilized to identify the characteristics of components, and a process of the FIS is shown in Figure 6.3.

When developing the FIS, membership functions for fuzzification and decision rules should be developed by designers' knowledge and companies' strategy. The inputs of FIS are crisp numbers of the risk value, degree of commonality, and sustainability value of components. Then, the inputs are fuzzified by using the membership functions. For fuzzy reasoning, fuzzy if-then rules are used. The output of each rule is a linear combination of input variables with a constant term based on Sugeno-type FIS [179]. A

typical rule in the Sugeno FIS is represented in equation (6.19). The final output of the system is the weighted average of all rule outputs.

$$\text{If input I1 is } x, \text{ and input I2 is } y, \text{ then output } z = ax+by+c. \quad (6.19)$$

Figure 6.3 Process of fuzzy inference system (adopted from [180])

The FIS results in four groups of the components for determining a sustainable platform: a sustainable and common, common, variant, and unique component. In the sustainable and common group, components have high sustainability value with high commonality, while components in the common group have high commonality and low risk. Components in the variant group have a medium level of commonality and risk value; components in the unique components have no commonality and high risk. Therefore, the sustainable platform can be identified in the sustainable and common group.

A case study was carried out to demonstrate the usefulness of the proposed method in next section.

6.7 Case study

A case study was performed with a family of coffee makers as shown in Table 6.3. The family of coffee makers has simple product architecture and mechanisms but it is still efficient. Product A (HD7450) is for home use, product B (HD7448) is for office use,

and product C (HD7458) is for office use. Specifications of the family of coffee makers are shown in Table 6.3. Philips coffee makers were disassembled for the case study and an explosive view of a coffee maker with components is described in Figure 6.4.

Table 6.3 Specification of a family of coffee makers

	Product A (HD7450)	Product B (HD7448)	Product C (HD7458)

Price	S\$42	S\$62	S\$89
Brewing time	< 10 minutes	9 minutes	< 10 minutes
Specification	220V, 50Hz, 650W 4-6 Cups (0.6 litres)	220V, 50Hz, 1000W 4-15 Cups (1.3 litres)	220V, 50Hz, 1000W 4-15 Cups (1.3 litres)

Figure 6.4 An explosive view of a coffee maker (Product B)

6.7.1 Phase 1 Aggregation of Indicator Data to a Sustainability Value

6.7.1.1 Identifying Sustainability Indicators for the Case Study

The proper sustainability indicators should be chosen to measure the sustainability of the coffee makers. As the significant effects on climate change are the biggest issue in environmental performance, greenhouse gases during the life cycle of the coffee maker have been selected as environmental indicators. Three critical greenhouse gases were selected as follows: CO₂ emission that is a representative GHG, nitrogen oxides including N₂O, and CFC-14 [181]. Simapro 8 software [182] was utilized to produce estimates of CO₂ in air (unit: *g*), nitrogen oxides (unit: *g*), and CFC-14 (unit: *mg*) for the coffee makers. The Simapro 8 assesses impacts of each environmental indicator based on the information on bill of material like material types, its weight, and a process type.

The LCC for the product family was considered as economic indicators. The LCC included costs over the product lifecycle that are material cost, production cost, transportation cost, use (service) cost, and end-of-life cost.

For social indicators, one of the most important factors was worker's health. Also, managing toxic substances for safe working environment demands social responsibility of companies. Accordingly, two influencing factors, Hg (Mercury) and SO₂ (Sulfur dioxide), were selected as social indicators to represent the worker's health according to the working environment in this study [183].

6.7.1.2 A Multi-Attribute Decision Making Approach for Comparison of Sustainability Values between Products in a Family

The sustainability values of each component in products A, B, and C were calculated by GRA. When deciding weight values on equations (6.14) and (6.15) of GRA calculation, AHP was applied to consider a hierarchical relationship between the

sustainability categories and indicators. This is because AHP helps decision making in a group of decision makers structure complex decisions and develop measure of preference [184]. Also, AHP can produce insightful results to difficult and real world decision problem as a decision making tool [185]. There are alternative methods to determine the weight value based on the preference of attributes from decision makers: multi attribute decision making (MADM) including simple additive weighting method (SAW) and multi attribute utility theory, and utility theory. Additionally, fuzzy-MADM like fuzzy-AHP and fuzzy-SAW can be applied to capture linguistic and fuzzy preferences of decision makers.

Accordingly, the weighed values of environmental and economic, and social categories were assigned to 0.445, 0.412 and 0.143, respectively, by using AHP. Under each category, each indicator has sub-weight values calculated by AHP as well. For example, the environmental category has three indicators of CO₂, CFC-14, and Nitrogen oxides with each sub-weight value, 0.428, 0.232, and 0.340, respectively. Accordingly, the final weight of each indicator was calculated by a product of weight of the category and sub-weight of each indicator. In this case study, GRA resulted in the sustainability values of each component as shown in Table 6.4. The sustainability values can be used to determine which component is sustainable. A trend of the results is that small and lightweight components with plastic material like one-way valve have higher sustainability values than other components in the product family.

In order to compare products in the family, GRA was utilized based on the total amount of each indicator's value. Then, sustainability values of each product are represented in Figure 6.5. For the result in Figure 6.5, the higher sustainability value is, the better performance is. Since product A had better environmental, economic, and social performances as shown in Figure 6.5, product A was the most sustainable product in this case study. On the other hand, product C had the lowest sustainability because of expensive cost, and low environmental and social performances.

Figure 6.5 Comparison of sustainability values in the family

Table 6.4 Sustainability values of each component from grey relational analysis

Part No.	Indicator	Environ.			Economic					Social		Sustain-ability value
		CO ₂	CFC-14	Nitrogen Oxides	Material cost	Manuf cost	Transport. cost	Use cost	EOL cost	SO ₂	Hg	
	Reference sequence	0	0	0	0	0	0	0	0	0	0	
	Weight	0.445			0.412					0.143		
	Sub-weight	0.428	0.232	0.340	0.342	0.274	0.160	0.118	0.106	0.571	0.429	
	Final weight	0.190	0.103	0.151	0.141	0.113	0.066	0.049	0.044	0.082	0.061	
A	1 Bottom cover	0.88	0.63	0.63	0.98	0.86	0.83	0.53	0.90	0.63	0.63	0.77
	2 Silicon ring	0.99	1.00	1.00	0.97	0.86	1.00	0.38	0.90	1.00	1.00	0.94
	3 Hot plate	0.96	1.00	0.88	0.97	0.58	0.87	1.00	0.90	0.93	0.49	0.87
	4 Casing for heater	0.91	0.71	0.72	0.98	0.86	0.88	0.97	0.90	0.71	0.72	0.84
	5 Heater	0.85	0.54	0.55	0.95	0.58	0.77	0.60	0.90	0.55	0.54	0.70
	6 Main cord	0.95	1.00	0.70	0.85	0.51	0.77	0.48	0.90	0.59	0.63	0.77
	7 Heater holder pin	0.99	1.00	0.97	1.00	0.51	0.96	0.98	0.90	0.98	0.79	0.92
	8 Water tube set	0.98	0.90	0.91	1.00	0.86	0.97	0.94	0.90	0.91	0.91	0.93
	9 One-way valve	1.00	1.00	1.00	1.00	0.86	1.00	0.97	0.90	1.00	1.00	0.98
	10 Silicon tube	0.85	1.00	0.91	0.74	0.51	0.94	0.88	0.52	0.92	0.95	0.82
	11 Water reservoir	0.71	0.36	0.36	0.93	0.86	0.62	0.58	0.90	0.36	0.36	0.62
	12 Steam sprout	0.98	0.92	0.93	1.00	0.86	0.97	0.98	0.90	0.93	0.93	0.94
	13 Filter basket	0.88	0.63	0.63	0.98	0.86	0.83	0.70	0.90	0.63	0.63	0.78
	14 Filter	0.98	0.92	0.92	1.00	0.86	0.97	0.50	0.90	0.92	0.92	0.92
	15 Lid of coffee maker	0.89	0.65	0.66	0.98	0.86	0.85	0.85	0.90	0.66	0.66	0.80
	16 Decanter	0.44	1.00	0.55	0.44	0.51	0.65	0.36	0.33	0.62	0.79	0.56
	17 Bottom casing	0.79	0.47	0.47	0.96	0.86	0.72	0.69	0.90	0.47	0.47	0.69
	18 Screw	1.00	1.00	0.99	1.00	0.79	0.98	1.00	0.37	0.99	0.89	0.94
B	19 Bottom cover	0.89	0.66	0.66	0.98	0.70	0.74	0.53	0.73	0.66	0.66	0.76
	20 Hot plate	0.97	1.00	0.89	0.97	0.51	0.87	1.00	0.90	0.94	0.50	0.87
	21 Casing for heater	0.92	0.74	0.74	0.99	0.86	0.89	0.96	0.90	0.74	0.74	0.85
	22 Heater	0.86	0.56	0.57	0.95	0.40	0.65	0.33	0.67	0.57	0.57	0.66
	23 Main cord	0.95	1.00	0.70	0.85	0.51	0.77	0.48	0.90	0.59	0.63	0.77
	24 Heater holder pin	1.00	1.00	0.99	1.00	0.51	0.99	0.98	0.90	1.00	0.93	0.93
	25 Heater clip	1.00	1.00	1.00	1.00	0.51	0.99	0.98	0.90	1.00	0.96	0.94
	26 Water tube set	0.97	0.88	0.89	0.99	0.86	0.96	0.94	0.90	0.89	0.89	0.92
	27 One-way valve	1.00	1.00	1.00	1.00	0.86	1.00	0.97	0.90	1.00	1.00	0.98
	28 Silicon tube	0.85	1.00	0.91	0.74	0.51	0.94	0.88	0.52	0.92	0.95	0.82
	29 Water reservoir	0.77	0.44	0.44	0.95	0.70	0.54	0.58	0.73	0.44	0.44	0.63
	30 Steam sprout	0.98	0.91	0.91	1.00	0.86	0.97	0.98	0.90	0.91	0.91	0.94
	31 Filter basket	0.82	0.52	0.52	0.96	0.70	0.73	0.65	0.73	0.52	0.52	0.69
	32 Filter	0.95	0.83	0.83	0.99	0.70	0.92	0.45	0.90	0.83	0.83	0.85
	33 Lid of coffee maker	0.92	0.72	0.72	0.98	0.86	0.88	0.85	0.90	0.72	0.72	0.84
	34 Decanter	0.33	1.00	0.44	0.33	0.42	0.33	0.36	0.33	0.51	0.71	0.47
	35 Bottom casing	0.75	0.41	0.41	0.94	0.70	0.50	0.69	0.73	0.41	0.41	0.62
	36 Screw	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.73	1.00	0.96	0.99
C	37 Bottom cover	0.85	0.56	0.56	0.97	0.70	0.65	0.53	0.73	0.56	0.56	0.70
	38 Hot plate	0.97	1.00	0.89	0.97	0.44	0.87	1.00	0.90	0.94	0.50	0.86
	39 Casing for heater	0.92	0.74	0.74	0.99	0.86	0.89	0.96	0.90	0.74	0.74	0.85
	40 Heater	0.86	0.56	0.57	0.95	0.39	0.65	0.33	0.59	0.57	0.57	0.65
	41 Main cord	0.95	1.00	0.70	0.85	0.51	0.77	0.48	0.90	0.59	0.63	0.77
	42 Heater holder pin	1.00	1.00	0.99	1.00	0.51	0.99	0.98	0.90	1.00	0.93	0.93
	43 Heater clip	1.00	1.00	1.00	1.00	0.51	0.99	0.98	0.90	1.00	0.96	0.94
	44 Water tube set	0.97	0.88	0.89	0.99	0.86	0.96	0.94	0.90	0.89	0.89	0.92
	45 Clip cover	0.99	0.96	0.97	1.00	0.86	0.99	0.98	0.90	0.97	0.97	0.96
	46 One-way valve	1.00	1.00	1.00	1.00	0.86	1.00	0.97	0.90	1.00	1.00	0.98
	47 Silicon tube	0.85	1.00	0.91	0.74	0.51	0.94	0.88	0.52	0.92	0.95	0.82
	48 Water reservoir	0.68	0.33	0.33	0.92	0.58	0.42	0.58	0.67	0.33	0.33	0.54
	49 Steam sprout	0.98	0.91	0.92	1.00	0.86	0.97	0.98	0.90	0.92	0.92	0.94
	50 Steel cover for water reservoir	0.96	1.00	0.87	0.99	0.51	0.85	1.00	0.90	0.93	0.46	0.86
	51 Filter basket	0.87	0.62	0.62	0.98	0.70	0.80	0.65	0.63	0.62	0.62	0.74
	52 Lid of coffee maker	0.89	0.66	0.66	0.98	0.86	0.85	0.85	0.90	0.66	0.66	0.80
	53 Decanter	0.35	1.00	0.46	0.35	0.33	0.40	0.36	0.33	0.53	0.72	0.47
	54 Bottom casing	0.77	0.43	0.44	0.95	0.66	0.53	0.69	0.73	0.44	0.44	0.63
	55 Screw	1.00	1.00	1.00	1.00	0.95	0.99	1.00	1.00	1.00	0.94	0.99

6.7.2 Phase 2 Product Dependency Analysis

The coffee makers were disassembled and then analyzed to understand components' dependencies and functional flows. The functional diagram of the coffee makers is shown in Figure 6.6 with material, energy, and signal flows. There are five main modules for the coffee makers, such as a bottom casing, water reservoir and water tube parts, heater, decanter, and filter. The modules are mainly performed to achieve the main function of the coffee maker that is to brew coffee with consistent steam supplement.

Figure 6.6 Functional diagram of the coffee maker

Bill of materials for the product family was developed including variants of components, material types, and the number of components in Table 6.5. Three digits “1, 2, and 3” were used to express commonality and variety of each component in the family. When a digit is the same over all products, it means that a component is shared with all products like silicon tube. When a digit is the same in two products, the component is shared in two products. Otherwise, components are used as unique components.

Table 6.5 Bill of materials for the coffee makers

Part #	Part name	# Req'd	Material	Manufacturing Process	Product A	Product B	Product C
1	Bottom cover	1	PP	Injection molding	1	2	3
2	Silicon ring	1	Silicon	Injection molding	1	-	-
3	Hot plate	1	steel	Forming	1	2	2
4	Casing for heater	1	PP	Injection molding	1	2	2
5	Heater	1	Aluminum	Extrusion/Forming	1	2	2
6	Main cord	1	Copper		1	1	1
7	Heater holder pin	1	Steel	Forming/Stamping	1	2	2
8	Heater clip	1	Steel	Forming	-	2	2
9	Clip cover	1	PP	Injection molding	-	-	1
10	Water tube set	1	PP	Injection molding	1	2	2
11	One-way valve	1	PP, rubber	Injection molding	1	1	1
12	Silicon tube	4	Silicon	Extrusion	1	1	1
13	Water reservoir	1	PP	Injection molding	1	2	3
14	Steam sprout	1	PP	Injection molding	1	2	3
15	Steel cover for water reservoir	1	Steel	Forming	-	-	1
16	Filter basket	1	PP	Injection molding	1	2	3
17	Filter	1	PP	Injection molding	1	2	-
18	Lid of coffee maker	1	PP	Injection molding	1	2	3
19	Decanter	1	Glass	Glass molding	1	2	3
20	Bottom casing	1	PP	Injection molding	1	2	3
21	Screw	7	Steel	Machining	1	2	2

6.7.3 Phase 3 Identification of Product Redesign Opportunities

The Bayesian network was used to represent conditional relationships among components when design changes were triggered from components. The Bayesian network for a coffee maker was built by Netica software from Norsys Software Corporation [186]. In this case study, the likelihood was decided by dividing the number of incoming and outgoing networks between two components over the total number of the networks of a product. Dependency between components was represented in Figure 6.7 (a) as an example. There are two parent nodes and one child node with each

conditional probability. Based on equation (6.16), noisy-OR distribution was used to simplify developing conditional probability table as shown in Figure 6.7 (b) and the conditional probability was calculated as followings:

$$\begin{aligned} P(\overline{A17} | A3, A4) &= [1 - P(A17 | A3)] \times [1 - P(A17 | A4)] \\ &= (1 - 0.34) \times (1 - 0.5) = 0.33 \end{aligned} \quad (6.20)$$

$$P(A17 | A3, A4) = 1 - P(\overline{A17} | A3, A4) = 0.67 \quad (6.21)$$

(a)

A3	A4	P(A17)	
		Redesign (T)	Stable (F)
F	F	0	1
F	T	0.5	1-0.5 = 0.5
T	F	0.34	1-0.34 = 0.66
T	T	1-(1-0.5)(1-0.34)=0.67	(1-0.5)(1-0.34)=0.33

(b)

Figure 6.7 (a) Dependent relationships between components (b) its conditional probability table by using noisy-or distribution for the Bayesian network

Finally, the Bayesian network with noisy-OR distribution was developed with main components in the coffee maker family in Figure 6.8. There are two states: the *redesign* state which shows that the node has to be redesigned because of a design change at dependent nodes, the *stable* state which is not affected by the design change.

The Bayesian network can update the likelihood of each component when a design change propagates. There are three core components, such as heater, water tube set, and water reservoir. The network in Figure 6.8 shows change propagation from the heater with 100% probability for redesign to other neighbor components in this case. The design change propagated from the heater to a hot plate with 69%, casing for heater with 83.2%, heater holder pin with 25%, silicon tube with 59.8% and main cord with 56% probability for redesign according to direct dependency on the heater. As to indirect propagation, a bottom casing and bottom cover were affected with 54.7% and 37.8% probability for the redesign, respectively. Accordingly, the casing for the heater had high possibility to be redesigned when the design of heater was changed. Otherwise, components that are not directly connected to the heater like a decanter, lid of the coffee maker, and filter were robust against the change to the heater design. Additionally, according to the Bayesian network, the redesign paths could be identified from the heater through the casing for the heater, the bottom casing, and the bottom cover. Consequently, decision-makers can predict components to be redesigned and corresponding redesign paths through the Bayesian network.

To determine the risk to redesign of each component when other design changes occurred, it was assumed that design changes start from the three core components individually. As a result, average and standard deviation for likelihood were obtained in Table 6.6. The bottom cover, heater holder pin, filter, and decanter were robust according to the design changes.

To calculate risk values with the average likelihood, the redesign cost for each component was assumed to be 80% of the cost for the LCC in equation (6.2). In order to reduce the sensitivity of the assumption when the portion of the cost is changed from 80% to other values, the redesign cost of each component was normalized as shown in Table 6.7. Based on equation (6.17), the risk of each component was calculated as shown in Table 6.7.

Figure 6.8 Bayesian network model of a family of the coffee makers

Table 6.6 Average likelihood index from design changes of three key elements

#	Part name	Likelihood when a design change initiated from			Average	STD
		Heater	Water tube set	Water reservoir		
1	Bottom cover	0.38	0.19	0.19	0.25	0.11
2	Hot plate	0.69	0.35	0.35	0.46	0.20
3	Casing for heater	0.83	0.42	0.42	0.55	0.24
4	Heater	1.00	0.50	0.50	0.67	0.29
5	Main cord	0.56	0.28	0.28	0.37	0.16
6	Heater holder pin	0.25	0.13	0.13	0.17	0.07
7	Water tube set	0.50	1.00	0.50	0.67	0.29
8	Silicon tube	0.60	0.66	0.68	0.65	0.04
9	Water reservoir	0.50	0.50	1.00	0.67	0.29
10	Steam sprout	0.37	0.40	0.47	0.41	0.05
11	Filter basket	0.33	0.33	0.67	0.44	0.19
12	Filter	0.22	0.22	0.44	0.29	0.13
13	Lid of coffee maker	0.24	0.24	0.47	0.31	0.14
14	Decanter	0.19	0.09	0.09	0.12	0.05
15	Bottom casing	0.55	0.27	0.27	0.37	0.16

Table 6.7 Risk index from average likelihood and normalized cost of each component

#	Part name	AVG_Likelihood	Normalized cost	Risk value
1	Bottom cover	0.25	0.79	0.20
2	Hot plate	0.46	0.83	0.38
3	Casing for heater	0.55	0.92	0.51
4	Heater	0.67	0.65	0.43
5	Main cord	0.37	0.71	0.26
6	Heater holder pin	0.17	0.85	0.14
7	Water tube set	0.67	0.94	0.62
8	Silicon tube	0.65	0.70	0.45
9	Water reservoir	0.67	0.75	0.50
10	Steam sprout	0.41	0.94	0.39
11	Filter basket	0.44	0.79	0.35
12	Filter	0.29	0.83	0.24
13	Lid of coffee maker	0.31	0.91	0.29
14	Decanter	0.12	0.36	0.04
15	Bottom casing	0.37	0.75	0.28

6.7.4 Phase 4 Identification of Sustainable Platform

Based on information from previous phases including the sustainability value of each component, commonality value, and risk value, a sustainable platform was identified to extend a conventional platform strategy for sustainable product family design. An ideal sustainable platform will have high sustainability, high commonality, and low risk according to product redesign in a family.

To determine the sustainable platform, fuzzy inference system (FIS) was applied. The first step of the FIS was to take the information that was crisp values as the input, and develop membership functions for determining appropriate fuzzy sets. Accordingly, typical Trap-Tri-Trapezoidal type of membership function was used to describe the crisp values for the degrees of commonality and sustainability, while Gbell-Gauss-Gbell type function was adopted for the crisp value of the risk in Table 6.8. In this case study, the zero-order Sugeno model ($a=b=0$, $c=constant$) was applied as the output membership function, so that the output level was constant. Subsequently, fuzzy rules were developed to provide a basis from which decisions can be made by classifying the input or controlling the output. The fuzzy rules are represented as the surface views in Figure 6.9. The surface view from the FIS shows the mapping graphically between any two

inputs, which are sustainability and commonality values in Figure 6.9 (a), risk and sustainability values in Figure 6.9 (b), and commonality and risk values in Figure 6.9 (c). Finally, the output was obtained with three types of inputs as shown in Table 6.9. According to the FIS results (ρ), the characteristics of components were classified as unique ($0 \leq \rho \leq 0.45$), variant ($0.45 < \rho \leq 0.60$), common ($0.60 < \rho \leq 0.85$), and sustainable and common ($0.85 < \rho \leq 1$). The range of the characteristics for the classification can be decided by design strategies and product redesign planning.

Table 6.8 Membership functions for input and output data

Features		Membership functions	
Input	Risk	Low	Gbell(0.38 3.45 0)
		Medium	Gauss(0.09 0.45)
		High	Gbell(0.25 3 1)
	Commonality	Low	Trap(0 0 0.2 0.45)
		Medium	Tri(0.2 0.55 0.85)
		High	Trap(0.65 0.8 1 1)
	Sustainability	Low	Trap(0 0 0.2 0.5)
		Medium	Tri(0.25 0.5 0.8)
		High	Trap(0.6 0.8 1 1)
Output	Characteristic*	Unique	0
		Variant	0.3333
		Common	0.6667
		Sustainable and common	1

* Unique component has no commonality and high risk; a variant component has medium level of commonality and risk value; a common component has high commonality or low risk; a sustainable and common component has high sustainability value with the characteristic of the common component.

(a)

(b)

(c)

Figure 6.9 Surface views of relationships between (a) sustainability and commonality inputs, and characteristics; (b) risk and sustainability inputs, and characteristics; (c) commonality and risk inputs, and characteristics

Table 6.9 Identification of components characteristics

#	Part name	Crisp input			FIS result	
		Risk	Commonality	Sustainability	Output	Characteristics
1	Bottom cover	0.20	0.33	0.76	0.631	Common
2	Hot plate	0.38	0.33	0.87	0.541	Variant
3	Casing for heater	0.51	0.67	0.85	0.548	Variant
4	Heater	0.43	0.67	0.66	0.445	Unique
5	Main cord	0.26	1.00	0.77	0.957	Sustainable & common
6	Heater holder pin	0.14	0.67	0.93	0.796	Common
7	Water tube set	0.62	0.67	0.92	0.592	Variant
8	Silicon tube	0.45	1.00	0.82	0.727	Common
9	Water reservoir	0.50	0.33	0.63	0.269	Unique
10	Steam sprout	0.39	0.33	0.94	0.529	Variant
11	Filter basket	0.35	0.33	0.69	0.431	Unique
12	Filter	0.24	0.33	0.85	0.668	Common
13	Lid of coffee maker	0.29	0.33	0.84	0.642	Common
14	Decanter	0.04	0.33	0.47	0.141	Unique
15	Bottom casing	0.28	0.33	0.62	0.268	Unique

In this case study, when determining a platform according to conventional method based on the only commonality, there were two platforms: main cord and silicon tube as shown in Table 6.10. As the proposed method considered not only commonality but also the sustainability values and product redesign opportunities, the proposed method could identify a sustainable platform. The sustainable platform consists of common components, and common and sustainable components as shown in Table 6.10. The common components contained five components that are a bottom cover, heater holder pin, silicon tube, filter, and lid of coffee maker. Main cord was selected as a sustainable component because the main cord is closed to the concept of an ideal sustainable platform according to FIS results.

Table 6.10 Platform types and its configuration

Platform type	Common components	Common and sustainable components
A current platform	Main cord, Silicon tube	-
A sustainable platform	Bottom cover, Heater holder pin, Silicon tube, Filter, Lid of coffee maker	Main cord

To verify the sustainable platform from the proposed method, it was assumed that designers applied the sustainable platform into the current product family design of the coffee makers. Then, the product family with the sustainable platform could be compared to the current product family with the conventional platform. The representative indicators, which were CO₂ emission for the environmental indicator, LCC for the economic indicator, and SO₂ for the social indicator, were selected for comparison between two products in a family in this case study. The results were shown in Figure 6.10. The material weights of the product family were reduced by 96.10 g; CO₂ emission during product lifecycle was decreased by 4.88 g; LCC of the product family was increased by \$ 0.25; and SO₂ was reduced by 2.44 g. If 100,000 product families with the sustainable platform were sold, the company can save around 9.6 tons of material, and reduce about 490 kg of CO₂ emission and 245 kg of SO₂, compared to the current product family with a current platform.

Figure 6.10 Comparison product families with a current platform and a sustainable platform

This case study reflects the main contribution of the proposed method. (1) The proposed method helps measure and compare sustainability values including environmental, economic, and social performances. Also, designers can compare each performance between products in a family of coffee makers. (2) The proposed method helps predict components to be changed and redesigned based on the risk value. As a design change of a platform can affect a product family design, the risk value is used to determine robust components in a coffee maker under product redesign condition. (3) The proposed method helps identify a sustainable platform. The sustainable platform is identified in light of sustainability and product redesign opportunities. The sustainable platform would be beneficial to sustainable product design.

6.8 Summary and Preview

Product redesign toward a sustainable product family gives rise to change propagation. When platform design is changed during product redesign processes, the change propagation can have a great impact on all product design in a product family. Accordingly, a new concept of the platform design is needed to improve current

platform identification methods by integrating the sustainability value and the risk value to the change propagation into the product family design. When it comes to understanding the degree of sustainability, indicators in three sustainability categories such as environmental, economic, and social categories were aggregated to a single sustainability value by using grey relational analysis. In order to quantify the robustness of components against the change propagation, the risk value was introduced and calculated by using Bayesian network. Bayesian network was utilized to estimate and update the likelihood of components when a design change propagates under uncertainty of product redesign. Fuzzy inference system was used to provide a basis of how characteristics of components can be decided, and determine a sustainable platform based on the sustainability, commonality, and risk values. The proposed method contributes to using the newly-considered design information to identify the sustainable platform that contains low negative environment impacts and low risk which minimizes future redesign cost and efforts in the product family design. A case study with a family of coffee makers was performed to demonstrate how to identify the sustainable platform.

The proposed method has two additional advantages. First, the method can help compare the degree of sustainability between products or product families by using grey relational analysis. It would help to distinguish which products are more sustainable. Second, the method can predict possible redesign paths with minimum redesign costs and detect unexpected change propagation. Also, it can give opportunities to designers for managing the change propagation while redesigning complex products.

The limitation of the proposed method is that it is difficult to express product design change over time because Bayesian network is developed by acyclic dependency relationships. Therefore, modeling change propagation is needed to be improved to describe dynamic product design change by using a dynamic Bayesian network. Since the sustainable platform design has been focused on the manufacturing of a product family, it should be extended for considering product recovery to prolong the product family lifecycle. Future research will focus on how to reflect customer needs for a

sustainable product family and how to enhance profits and environmental performances of the sustainable product family.

The future work in this chapter has researched in next chapter. Chapter 7 introduced a multiobjective design optimization model to determine a configuration of sustainable product family based on customer preference, profits, and environmental impacts of products.

Chapter 7. Sustainable Product Family Identification Based on an End-of-life Platform Strategy

This chapter provides a multiobjective design optimization for identifying a configuration of sustainable product family design. It is assumed that products in a product family have eco-modules and the eco-modular architecture from Chapter 5. Based on this assumption, this chapter has focused on selecting module instances and combining the module instances for a sustainable product family configuration. Section 7.1 is an overview of this chapter. In Section 7.2, the product family configuration is described based on product family information from Step 1, and an end-of-life (EOL) platform is introduced. Although the sustainable platform from Chapter 6 is introduced for sustainable manufacturing, the sustainable platform has not focused on product recovery at the EOL stage. Therefore, the platform concept is extended to the EOL platform from the viewpoint of the EOL stage. Based on the EOL platform strategy, remanufactured products can be produced for prolonging product lifecycle. Then, the proposed method is mathematically formulated to determine new and remanufactured products configurations as a sustainable product family based on a trade-off between profits and environmental impact in Section 7.3. A case study is carried out to evaluate the method in Section 7.4 and the results from the case study are discussed in Section 7.5. Section 7.6 presents summary and preview.

7.1 Overview of the Sustainable Product Family

As the environmental problems are an extensive and complex problem, existing studies in various fields of engineering are researching about energy consumption, material/resource use, product recovery, and eco-design to solve and prevent the problem during product lifecycle. Accordingly, a variety of environmental regulations have been developed to encourage designers and manufacturers to take stronger

environment stewardship in product development. The environmental regulations, such as the Waste of Electrical and Electronic Equipment (WEEE), Energy Using Product (EuP), and End-of-Life Vehicles (ELV), are introduced to concern fabrication and disposal of products in terms of the environmental impact [7].

In the field of product design, eco-product design and product recovery strategy have been researched to consider the environmental issues with the product lifecycle. The eco-product design has mainly focused on reducing environmental impact. Furthermore, the eco-design studies mainly aim to develop eco-design tools to assess the environmental impact for single product [1, 39]. In order to improve the sustainability of products, other previous studies have emphasized product recovery strategies in the end-of-life stage. The product recovery strategy can be a promise solution to reuse or resale after recovering the used products. Especially, remanufacturing is one of the most effective and efficient ways of the product recovery strategy to recover used products to like-new condition, resulting in saving the use of raw materials and energy [187, 188]. Accordingly, reusing remanufactured modules would offer an opportunity for manufacturers to retrieve an economic value of the modules instead of disposal of the modules [108]. The remanufactured modules are able to widen the scope of product portfolio in a product family so that the product family covers more market segments than producing only new products [189].

In terms of economic performance of the sustainability, product family design has been focused on economic benefit by reducing development efforts and improving competitiveness and differentiation. A product family has a similar technical system to achieve similar functionality and is continuously evolved by determining trade-off between commonality and differentiation. Accordingly, the product family design and a platform strategy provide the benefit for companies, such as reducing lead time and product cost, improving upgradability and maintenance, and enhancing disassemblability based on modular architectures [164]. In this respect, the product family design provides sufficient product variants for different market segments with

keeping economies of scale and scope within manufacturing processes [20]. In this sense, the product family design has the potential for providing an opportunity to share remanufactured modules among product variants for maintaining and upgrading performances.

However, although the eco-design and the product family design have been well researched individually, it is still developing to link the eco-design and the product family design. In order to develop a sustainable product family, the need for new methods to redesign current product family configuration by integrating sustainability performance into the product family design becomes essential. Designing the sustainable product family entails the new concept of platform design, product family configuration with new and remanufactured modules, and sustainability performance. Therefore, this study proposes a method to identify a sustainable product family configuration by integrating a product recovery strategy, especially remanufacturing, and a platform strategy based on a multiobjective optimization model. For the research, remanufacturable modules are identified according to their recovery costs and performances. It means that the performance and costs of the remanufacturable modules are affordable to reuse or resale. However, although modules can be remanufactured, the modules may be difficult to be shared to keep or upgrade their performance because the modules are not compatible in terms of spatial, functional, and interface restrictions. In this sense, an EOL platform is determined by assessing the spatial, functional, and interface compatibility from the viewpoint of end-of-life stage. The EOL platform contributes to enhancing reusability of the modules so that the usage of raw material, environmental impact, and lifecycle cost can be reduced. Also, it is a baseline to configure a sustainable product family with new and remanufactured modules. For the configuration of the sustainable product family, design information related to sustainability performance is concerned rather than only considering environmental impact as follows: (1) profits of new and remanufactured product variants as economic performance, (2) customer demands as social performance, and (3) environmental

impact of manufacturing and remanufacturing as environmental performance. The design information is mathematically modelled to acquire quantitative measures in the form of a multiobjective optimization model. The model results in the configuration of the product family with both new and remanufactured modules by Non-dominated Sorting Genetic Algorithm (NSGA-II). Thus, this study shows how a product family can reduce negative environmental impact while keeping profit by reusing remanufactured modules.

7.2 Problem Description of Sustainable Product Family Design

In this research, a sustainable product family is defined as a product family with considering an EOL platform and sustainability performance to reduce harmful effect on users and environment. This study considers manufacturers that can produce new products and remanufactured products for prolonging product lifecycle and enhancing the sustainability of the product family. As shown in Figure 7.1, firstly, a sustainable product family is planned based on analysis of an existing module-based product family. Modules can be configured according to designer's intent which focuses on disassemblability, recyclability, and reusability to enhance efficiency and effectiveness of manufacturing and remanufacturing processes [9]. Secondly, an EOL platform can be decided to determine whether or not the modules can be shared in the product family to maintain and upgrade functionality at the end-of-life stage. Also, the expected performance and redesign costs for modules are measured to check whether or not the modules are capable of remanufacturing economically and functionally. Finally, based on the EOL platform and the modules, an optimization model is developed to determine the configuration of a sustainable product family. The sustainable product family is a combination of new and remanufactured modules to achieve the sustainability goal which is to minimize environmental impact and maximize profits with considering customer demands.

Figure 7.1 Overview of sustainable product family identification

7.2.1 Product Family Analysis

A product family is developed to satisfy different customers in a market. The customers may have different preferences for product profiles. As shown in Figure 7.2, markets can be clustered into i th market segment (S_i , $i=1, \dots, I$) with the demand of products (D_i) [20, 89, 190, 191]. To satisfy a variety of the market segments, a product family contains multiple product variants, represented as P_j ($j=1, \dots, J$) [191, 192]. The product variants in the family would have similar product architecture, module, and component with similar functionalities, but a different level of performances or features for customer satisfactions. Each product variant is composed of various modules (M_k , $k=1, \dots, K$). Each module has different attributes and is fully replaceable. Module instances in k th module are indexed as l ($l=1, \dots, L_k$). L_k is the number of the module instances. The module instances with different attributes make more variety of products to satisfy market segments. On the other hand, a platform that is a set of common modules in existing product family design is shared with fixed attribute levels to save

lead time and cost for manufacturing. Therefore, module configurations based on the module instances and the platform enable the product family to be differentiated.

Figure 7.2 Product family configuration with various module instances

To be sustainable by reusing modules in the product family, the product family and a platform strategy have to be reconsidered from the viewpoint of end-of-life (EOL) stage. In the EOL stage, although the module instances are not a platform for a product family for the manufacturing, the module instances can provide a chance to be replaced between products as shown in Figure 7.3. For example, there are three product variants in a family, (P_1, P_2, P_3) . Each product variant is configured with a combination of four modules (M_1, M_2, M_3, M_4) . Modules 1, 2, and 4 have three instances, while module 3 has a single module. If l th module instance represents performance level in k th module (M_k) , the third instance of module 1 (M_{13}) has high performance among module instance in module 1 (M_1). The M_{13} can be substituted for first (M_{11}) and second instance (M_{12})

to configure product variants (P_1 and P_2). Module instances in M_2 are also replaceable like M_1 . However, M_4 that is unique modules is not replaceable at the end-of-life stage. Therefore, M_1 , M_2 , and M_3 are called as the replaceable modules [109]. Since the first instance of module 3 (M_{31}) is shared in all product variants, M_{31} can be regarded as a conventional platform of the product family. The EOL platform stands on the concept of the replaceable module and the platform. Furthermore, the compatibility of each module instance is analyzed to reuse the module instances for configuring remanufactured products from the viewpoint of the EOL stage. The detailed explanation for the EOL platform is in the following section.

Figure 7.3 Replaceable modular architecture and EOL platform

7.2.2 End-of-life Platform Identification

The new concept of a platform called as ‘an EOL platform’ is introduced in this section. The EOL platform is defined as a set of components or modules that can be reused between products based on spatial, functional, and interface compatibilities. There are differences between a conventional modular platform and an EOL platform. The conventional modular platform is identified based on commonality and has fixed design feature and performance. However, the EOL platform can be not only common modules

but also the replaceable modules that can be reused in a product family to perform products' functionality. Namely, although the module instances are not the conventional modular platform because of different design features and performances, it can be shared between other products in the family like M_1 , M_2 , and M_3 in Figure 7.3. The concept of the EOL platform emphasizes on product recovery activities at the EOL stage.

Since the EOL platform can be shared between high-performance products and low-performance products like M_1 and M_2 in Figure 7.3, it seems to be similar with a scalable platform. The scalable platform stretches a common modular platform by varying one or more of its design parameters for customization [31]. The scalable platform contains modules with different capability and size, for example, Rolls Royce RTM 322 engine and Black & Decker's universal motors [31]. Accordingly, the scalable platform can be shared in a product family but not all. On the other hand, the EOL platform can be shared for configuring remanufactured products based on compatibility of each module at the EOL stage.

The compatibility between different module instances can be checked based on following three aspects: (a) Functional compatibility (FC), (b) Spatial compatibility (SC), and (c) Interface compatibility (IC). Accordingly, designers can develop compatibility matrix of all module instances in a product family as shown in Table 7.1. For example, there are two modules (M_1 and M_2) that include two module instances, respectively. If M_{11} is compatible with M_{12} in terms of each compatibility, the element of the compatibility matrix, $C(M_{11}, M_{12})$, is equal to 1. Otherwise, $C(M_{11}, M_{12})=0$ as shown in Table 7.1 (a). First of all, FC is critical to EOL platform identification. When functions between retired modules and remanufactured modules are compatible, the remanufactured module can be reused to maintain products and upgrade the functions of the products. Although the functions of the remanufactured modules are compatible with module instances within the same module, e.g., two electric motors with different capacities (M_{21} and M_{22}) within the same module (M_2), other neighbor module instances in different modules that have functional relationship with the remanufactured modules

may not be compatible when capabilities of these module instances cannot support performing the functions of the remanufactured module. Accordingly, FC is needed to be measured among all module instances as shown in Table 7.1 (a). Secondly, the SC is measured between module instances within a module. The SC aims to check whether or not a module instance can be substituted for the remanufactured or new module instance regardless of spatial constraints for assembly operations in Table 7.1 (b). Thirdly, the IC is needed to check whether or not the replaced module can be assembled between modules in terms of interface types and locations in the module as shown in Table 7.1 (c). Based on these three compatibility matrices, a total compatibility matrix is developed after building the compatibility matrix within modules and between modules, respectively. For developing the compatibility matrix within the modules, AND operator of the Boolean algebra ($FC \cap SC \cap IC$) is applied as shown in Table 7.1 (d) because the module instances within each module could not be compatible if one of these three compatibilities is not satisfied. On the other hand, for analyzing the compatibility between modules, a combination of AND and OR operators is applied as $((FC \cap IC) \cup SC)$. This is because the SC is focused on the compatibility of module instances within the same modules. Accordingly, the SC between modules is always 0. Table 7.1 (e) shows the result between different modules. Therefore, total compatibility matrix in Table 7.1 (f) is developed by combining the matrix in Table 7.1 (d) and (e). From the total compatibility matrix, an EOL platform can be identified, which is compatible with all products in a product family in terms of function, space, and interface. In this sense, M_{12} can be an EOL platform.

Table 7.1 Compatibility matrices

(a) Functional compatibility (FC) between entire module instances

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	1	1	0	1
M ₁₂	1	1	1	1
M ₂₁	0	1	1	1
M ₂₂	1	1	1	1

(b) Spatial compatibility (SC) within instances of the same module

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	1	1	0	0
M ₁₂	1	1	0	0
M ₂₁	0	0	1	1
M ₂₂	0	0	1	1

(c) Interface compatibility (IC) between entire module instances

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	1	1	0	1
M ₁₂	1	1	1	1
M ₂₁	0	1	1	0
M ₂₂	1	1	0	1

(d) Compatibility within modules

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	1	1	-	-
M ₁₂	1	1	-	-
M ₂₁	-	-	1	0
M ₂₂	-	-	0	1

(e) Compatibility between modules

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	-	-	0	1
M ₁₂	-	-	1	1
M ₂₁	0	1	-	-
M ₂₂	1	1	-	-

(f) Total compatibility of module instances

	M ₁₁	M ₁₂	M ₂₁	M ₂₂
M ₁₁	1	1	0	1
M ₁₂	1	1	1	1
M ₂₁	0	1	1	0
M ₂₂	1	1	0	1

7.3 Modelling for a Sustainable Product Family

For designing a product family to be more sustainable, designers should consider environmental impact. After product design, every stage of product lifecycle, which is from raw material extraction stage to disposal stage, causes environmental impact extensively. Since a company is difficult to enhance efficiency of manufacturing facilities for minimizing the environmental impact of investment for adopting advanced technologies, the environment-concerned design could be a possible solution for the company to make products more sustainable by choosing eco-friendly materials and/or recycled materials, and designing product architectures to enhance remanufacturing processes. In this chapter, three representative indicators of each sustainability aspect, such as environmental impact, profit, and customer preference, were selected to configure a sustainable product family. Although there are difficulties considering sustainability aspects simultaneously, this study could be a good starting point for sustainable product design. Since many researchers and manufacturers have still more interested in profits than environmental impact, this study could be worth showing new research directions to consider sustainability in a product design stage.

The overall optimization procedure to identify sustainable product family configuration is summarized in Figure 7.4 and Table 7.2. Design variables are defined in Section 7.3.1. Section 7.3.2 is to estimate production demand of a product family (Q) from two types of markets: market segments for new products and a market segment for remanufactured products. Using a multinomial logit choice model, choice probability of each market segment is calculated. Then, the production demand of new or remanufactured products can be expected by multiplying the choice probability and demands of all product variants including products of competitors. Based on the production demand, objective functions and constraints are modelled to determine configuration of a sustainable product family in sections 7.3.3, 7.3.4, and 7.3.5. The output of the proposed model is the configuration of new products, remanufactured

products with a combination of new and remanufactured modules, brand-leaders that are the best-selling products in current markets, and profit and environmental impacts as shown in Table 7.2.

Figure 7.4 Overview of the optimization model to identify a sustainable product family configuration

Table 7.2 The proposed sustainable product family design optimization model

<p>Given</p> <ul style="list-style-type: none"> • Module instances to configure a product family • Estimated part-worth utility for new and remanufactured products • Process cost and price • Market size • Estimated environmental impact by Eco-indicator 99 <p>Output:</p> <ul style="list-style-type: none"> • Brand leaders in current markets • New product configuration, remanufactured product configuration • Environmental impact • Profit <p>Objective: Configurations of new and remanufactured products in a product family based on:</p> <ul style="list-style-type: none"> • Maximize (profits from new products + profits from remanufactured products) • Minimize (environmental impact over product lifecycle) <p>Subject to:</p> <ul style="list-style-type: none"> • One of module instances in a module is selected. • The expected sales volume of products should be less than market demand. • Reliability of remanufactured products should be satisfied by company regulations. <p>Assumptions</p> <ul style="list-style-type: none"> • Accumulated preference data are available. • Remanufacturing of modules is possible. • Brand-leader and competitors' products affect the sales volume of products and product configurations.
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7.3.1 Design Decision Variable

The problem description of the sustainable product family can be translated to determination of proper module instances for configuring the product family. For the mathematical modelling, the following binary design decision variables are defined:

$$x_{jkl} = \begin{cases} 1 & \text{if } l\text{th module instance is used in } k\text{th module of } j\text{th product variant} \\ & (j=1,2,\dots,J; k=1,2,\dots,K; l=1,2,\dots,L) \\ 0 & \text{otherwise} \end{cases}$$

$$X_j = \begin{cases} 1 & \text{if } j\text{th product variant is produced} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{jkl} = \begin{cases} 1 & \text{if } l\text{th module instance is used in } k\text{th module of } j\text{th remanufactured product variant} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_r = \begin{cases} 1 & \text{if } r\text{th remanufactured product is produced} \\ 0 & \text{otherwise} \end{cases}$$

$$z_{jkl} = \begin{cases} 1 & \text{if } l\text{th module instance of } k\text{th module in } j\text{th product variant is remanufacturable} \\ & \text{(if } QL_{jkl} \geq 1) \\ 0 & \text{otherwise} \end{cases}$$

x_{jkl} and y_{jkl} are binary decision variables to know whether or not a module instance is selected in new or remanufactured product variants, respectively.

As all modules and/or products at the EOL stage are difficult to reuse because of their quality, binary decision variable z_{jkl} is needed to decide whether the modules will be remanufacturable or not. So, quality of a replaceable module (QL) should be evaluated for decision making of remanufacturability. There are two critical factors for assessing the QL: performance ($Perf_{jkl}$) and recovery cost (C_{jkl}^{rem}). Firstly, the performance is a key factor for decision making of product recovery strategies. If the performance satisfies requirements of a company ($Perf_{jkl(b)}$), the modules have high chance to be recovered and then reused. Otherwise, the modules would be recycled or discarded. As measuring performance is also a challenging issue, the measuring performance is simplified as shown in equation (7.1) and Table 7.3 [193]. Secondly, after selecting well-performing modules, the company will decide marginal threshold of remanufacturing cost ($C_{jkl(b)}^{rem}$) for product recovery. If the remanufacturing cost is higher than the threshold although the performance is satisfied, the modules will not be remanufactured. Accordingly, when the QL of the EOL modules is more than threshold value ($QL \geq 1$), the EOL modules represent sufficient performance and affordable remanufacturing cost, so that the EOL module can be selected to be remanufactured ($z_{jkl} = 1$). Otherwise, it would be better to buy or manufacture new modules ($z_{jkl} = 0$).

$$QL_{jkl} = \left(\frac{Perf_{jkl}}{C_{jkl}^{rem}} \right) / \left(\frac{Perf_{jkl(b)}}{C_{jkl(b)}^{rem}} \right) \quad (7.1)$$

Table 7.3 Performance assessment

Performance indices	Satisfy	Not satisfy
Perf (A _{jkl}) (ex, power)	A _{jkl} =A _{jkl(b)} , Perf=1	A _{jkl} <A _{jkl(b)} , Perf=(A _{jkl} /A _{jkl(b)}) ²
Perf (B _{jkl}) (ex, battery)	B _{jkl} =B _{jkl(b)} , Perf=1	B _{jkl} <B _{jkl(b)} , Perf=(B _{jkl} /B _{jkl(b)}) ²
Perf (C _{jkl}) (ex, capacity)	C _{jkl} =C _{jkl(b)} , Perf=1	C _{jkl} <C _{jkl(b)} , Perf=(C _{jkl} /C _{jkl(b)}) ²

7.3.2 Modelling Customer Preference and Expected Demand

For selecting product variants, customer preference of products in market segments can be analyzed according to the utility value of each product in market segments [113]. Conjoint analysis can be applied to evaluate utilities and result in linear function with part-worth utilities of products [112]. The utility of new j th product variant in the i th market can be described in equation (7.2). The utility consists of an observable deterministic component that is the first term of the equation, and a part unobserved (ε), called as a stochastic error component.

$$U_{ij}^N = \sum_{k=1}^K \sum_{l=1}^{L_k} w_i u_{kl} x_{jkl} + \varepsilon_{jkl}^N \quad (7.2)$$

Where w_i is the weight of i th market segment, and u_{kl} is the part worth utility of l th instance of the k th module. When reusing remanufactured modules, the part-worth utilities of remanufactured product can be represented as following equation [108].

$$U_{ij}^R = \sum_{k=1}^K \sum_{l=1}^{L_k} w_i (u_{kl} y_{jkl} + v_{kl} z_{jkl}) + \varepsilon_{jkl}^R \quad (7.3)$$

Here, v_{kl} is the part-worth utility of the remanufactured l th module attributes of k th used module in the EOL stage. When selecting a module instance for a remanufactured product, the utility of the module instances is the sum of v_{kl} and the u_{kl} . Otherwise, the part-worth utility for remanufactured products can be the same as the utility for new products (u_{kl}) in a market segment.

A discrete choice model is applied to describe choices of decision makers (customers) among alternatives (products) [194, 195]. The set of alternatives has to satisfy three characteristics for fitting a discrete choice framework as follows [196]: (1) mutually exclusive alternatives from the perspective of the decision makers, (2) exhaustive set of the alternatives, and (3) finite number of alternatives. The first and second criteria are not restrictive [196]. The discrete choice model including a logit model and a probit model is a basis of various probabilistic choice models for representing customer behaviour. However, there is a difference between the logit model and the probit model that are widely used discrete choice model because the models are derived from the different assumption of the error component. The probit model has an assumption that the error component is normally distributed. The probit model produces similar results with the logit model. The main advantage of the probit model is flexibility on dealing with correlation over alternatives and time. However, the assumption makes the probit model difficult to estimate, interpret, and predict because of numerical problems. It means that the model leads to unreasonable forecasts when the normal distribution is inappropriate [197]. On the other hand, the logit model has independent from irrelevant alternatives (IIA) property in order to provide an accurate representation of reality. The property helps estimate parameters of logit model consistently on a subset of alternatives for each decision maker, and examine choices among a subset of interesting alternatives, not all alternatives [196]. It would reduce computational time and expense. Therefore, the logit model is used in this study. In the logit model, a multinomial logit choice model (MNL) has been chosen to model

customer preference derived from utility maximization behaviour, and then forecast market demand of products. The MNL is the easiest and most widely used discrete choice model [196]. It provides the choice probability of each alternative to reflect realistic customer behaviour of purchasing decision making because of the principal assumption of the MNL [198]. The principal assumption of the MNL is that the error component is Gumbel distributed, and is identically and independently distributed for alternatives. The Gumbel distribution is used to approximate closely normal distribution and yields a closed-form solution that leads to a computational advantage [194, 195]. In summary, the MNL is applied to this study because of its advantages such as simplicity, interpretability, and its capability of extending the choice probability into new product design development [194, 196, 199].

In order to estimate demands for products in market segments, the choice probability of customers can be estimated by the MNL. For example, when there are three products ($j=1,2,3$) in 1st market segment ($i=1$), a choice probability of 1st new product ($j=1$) in the 1st market segment can be modelled as followings.

$$P_{11} = e^{U_{11}^N} / \sum_{j=1}^3 e^{U_{1j}^N} \quad (7.4)$$

By extending the MNL, the estimated choice probability of both new and remanufactured products in i th market segment (P_i) can be formulated as follows:

$$P_i = \frac{\sum_j^J X_j \cdot e^{U_{ij}^N} + \sum_j^{R'} Y_j \cdot e^{U_{ij}^R}}{\sum_j^J X_j \cdot e^{U_{ij}^N} + \sum_j^{R'} Y_j \cdot e^{U_{ij}^R} + \sum_j^C e^{U_{ij}^{Co}}} \quad (7.5)$$

Where the amount of new product variants provided is J , the number of remanufactured product to be provided is J' , and the number of competitors' products is J'' . The number of different products in the market can be $(J+R'+C)$. X_j and Y_j are

variables that indicate whether or not j th product variant is produced. Then, the expected demand for the product (Q) can be calculated by the product of the choice probability (P_i) and a total number of products in markets (D_i) as following:

$$Q = \sum_i^I D_i \cdot P_i \quad (7.6)$$

Equation (7.6) is divided into expected production demand of new products in equation (7.7) and remanufactured products in equation (7.8).

$$Q_{new} = \sum_i^I D_i \frac{\sum_j^J X_j \cdot e^{U_{ij}^N}}{\sum_j^J X_j \cdot e^{U_{ij}^N} + \sum_j^{R'} Y_j \cdot e^{U_{ij}^R} + \sum_j^C e^{U_{ij}^{Co}}} \quad (7.7)$$

$$Q_{rem} = \sum_i^I D_i \frac{\sum_j^{R'} Y_j \cdot e^{U_{ij}^R}}{\sum_j^J X_j \cdot e^{U_{ij}^N} + \sum_j^{R'} Y_j \cdot e^{U_{ij}^R} + \sum_j^C e^{U_{ij}^{Co}}} \quad (7.8)$$

7.3.3 A Product Family Profit Model

First objective is to maximize the profit of a product family including new and remanufactured products. Manufacturers' first priority is to enhance their profit. A product family profit model is formulated in equation (7.9). As it aims to maximize profits during lifecycle of the product family, the product family profit is calculated by the sum of profits of new products and remanufactured products. The profit from new products is formulated with manufacturing and selling Q_{new} units of new products in equation (7.10). Equation (7.11) formulates the end-of-life profit from remanufacturing products with remanufacturing Q_{rem} units. Process prices and costs are modelled in equations (7.12) through (7.16). Based on binary design variables for new module

instance selection (x_{jkl}) and remanufactured module instance selection (y_{jkl}), configurations of new and remanufactured product variants can be determined, respectively. When developing a new product with considering profit and environmental impact of a remanufactured product, this proposed model can suggest the sustainable product variants by setting $x_{jkl} = y_{jkl}$. Equation (7.16) is developed to calculate remanufacturing cost of each module instance based on work by Zhang and Gershenson [200], where i is the discount rate, and t_{eol} is time between manufacturing and remanufacturing of products.

$$\text{Maximize Profit} = f_1^N + f_1^R \quad (7.9)$$

$$f_1^N = (P^{new} - C^{new})Q_{new} \quad (7.10)$$

$$f_1^R = (P^{rem} - C^{rem})Q_{rem} \quad (7.11)$$

$$P^{new} = \sum_j \sum_k \sum_l p_{jkl}^{new} x_{jkl} \quad (7.12)$$

$$P^{rem} = \sum_j \sum_k \sum_l p_{jkl}^{rem} y_{jkl} z_{jkl} \quad (7.13)$$

$$C^{new} = \sum_j \sum_k \sum_l c_{jkl}^{new} x_{jkl} \quad (7.14)$$

$$C^{rem} = \sum_j \sum_k \sum_l c_{jkl}^{rem} y_{jkl} z_{jkl} \quad (7.15)$$

$$c_{jkl}^{rem} = (1+i)^{t_{eol}} \cdot (C_{jkl}^{disassy} + C_{jkl}^{condition} + C_{jkl}^{rem} + C_{jkl}^{assy}) \quad (7.16)$$

7.3.4 Environmental Impact of Module Instance

The second objective is to minimize environmental impact (EI) of the product family. Producing products damages the environment over product lifecycle, which is raw

material production, production, transportation, energy consumption while using products, and disposal stages. Accordingly, lifecycle phases must be studied to assess EI. However, it is difficult to establish lifecycle assessment model for measuring EI because of various categories and diverse calculation methods of the EI. In this research, Eco indicator 99 which is one of the popular methods is used to measure EI of each component. Eco-indicator 99 contributes to three environmental damage categories: human health, ecosystem quality, resources [138]. Total EI of a product family is linked to module instance configurations of product variants, and production quantity of the product variants (Q). The total EI is determined by summing EI values of each product lifecycle stage (e_{jkl}) as shown in equation (7.18). The EI is assessed by a product of the EI value of each stage, material weight (m_{jkl}), and the expected demand (Q_{new} and Q_{rem}). In the EOL stage, the EI of the remanufactured modules ($z_{jkl} = 1$) considers only EI from transport, energy from remanufacturing process, and waste as shown in equation (7.19). Using remanufactured modules in a product can lessen the EI rather than using new modules. Otherwise, when a new module ($z_{jkl} = 0$) is used for configuring the product, the EI in the EOL stage is the same as the EI in equation (7.18).

$$\text{Minimize } EI = EI^{NEW} + EI^{EOL} \quad (7.17)$$

$$\begin{aligned} EI^{NEW} &= \sum_j \sum_k \sum_l (e_{jkl}^{material} + e_{jkl}^{production} + e_{jkl}^{transport} + e_{jkl}^{energy} + e_{jkl}^{EOL}) m_{jkl} x_{jkl} Q_{new} \\ &= \sum_j \sum_k \sum_l E_{jkl}^{new} m_{jkl} x_{jkl} Q_{new} \end{aligned} \quad (7.18)$$

$$\begin{aligned}
EI^{EOL} &= \left(\sum_j \sum_k \sum_l (e_{jkl}^{material} + e_{jkl}^{production} + e_{jkl}^{transport} + e_{jkl}^{energy} + e_{jkl}^{EOL}) m_{jkl} y_{jkl} (1 - z_{jkl}) + \right. \\
&\quad \left. \sum_j \sum_k \sum_l (e_{jkl}^{transport} + e_{jkl}^{energy} + e_{jkl}^{EOL}) m_{jkl} y_{jkl} z_{jkl} \right) Q_{rem} \\
&= \left(\sum_j \sum_k \sum_l E_{jkl}^{new} m_{jkl} y_{jkl} (1 - z_{jkl}) + \sum_j \sum_k \sum_l E_{jkl}^{rem} m_{jkl} y_{jkl} z_{jkl} \right) Q_{rem}
\end{aligned} \tag{7.19}$$

7.3.5 An Optimization Model for Identifying a Sustainable Product Family

Based on the above-mentioned objective functions, the proposed model can be established as following:

Objectives

$$\text{Max } \sum_j \sum_k \sum_l (p_{jkl}^{new} - c_{jkl}^{new}) x_{jkl} Q_{new} + \sum_j \sum_k \sum_l (p_{jkl}^{rem} - c_{jkl}^{rem}) y_{jkl} z_{jkl} Q_{rem} \tag{7.20}$$

Min

$$\sum_j \sum_k \sum_l E_{jkl}^{new} m_{jkl} x_{jkl} Q_{new} + \left(\sum_j \sum_k \sum_l E_{jkl}^{new} m_{jkl} y_{jkl} (1 - z_{jkl}) + \sum_j \sum_k \sum_l E_{jkl}^{rem} m_{jkl} y_{jkl} z_{jkl} \right) Q_{rem} \tag{7.21}$$

Subject to

$$\sum_j (X_j + Y_j) \leq \dot{X} \tag{7.22}$$

$$R_j = \exp[-t_{eol} \times \sum_j \sum_k \sum_l \lambda_{kl} y_{jkl}], \quad R_j \geq \varepsilon \tag{7.23}$$

$$Q_{new}, Q_{rem} \in \text{nonnegative integer} \tag{7.24}$$

$$\sum_l x_{jkl} = 1, \sum_l y_{jkl} = 1, \quad \forall j, \forall k \tag{7.25}$$

Where, equation (7.22) constrains that the number of new and remanufactured products is less than the number of $\bar{X}$ which is total number of product variants in the market. Since reliability of remanufactured modules may be declined, the remanufactured modules should satisfy reliability requirement (ε). Otherwise, the recovered modules cannot be reused. The reliability of the product can be represented as exponential function with failure rate (λ) and time between manufacturing and remanufacturing (t_{eol}) [201, 202]. The reliability is represented as a constraint when selecting module instances for a product family as shown in equation (7.23). Equation (7.25) represents that a l th module instance is selected in k th module for new and/or remanufactured products, respectively.

7.3.6 An Optimization Tool

In product family design, multiobjective optimization is used to capture the Pareto frontier and to determine the best design variable setting for products of a family based on the Pareto frontier [203]. Metaheuristic algorithms, especially, evolutionary algorithms like a genetic algorithm for multiobjective optimization [204] and particle swarm optimization [90], can be employed to solve multiobjective optimization problems by customizing design problems to deal with objectives and constraints. One of the widely used evolutionary algorithms under multiobjective optimization problems is a non-dominated sorting genetic algorithm (NSGA-II). The NSGA-II algorithm was developed to solve the multiobjective optimization problems. It can deal with high dimensional and more difficult multiobjective optimization problems, so that it would be suitable for product family design problems [203]. The NSGA-II can find a Pareto front and obtain Pareto optimal solutions better than other multiobjective evolutionary

algorithms like vector evaluated GA (VEGA), niched Pareto GA (NPGA), and multiobjective GA (MOGA) [205]. Therefore, the NSGA-II is applied to developing sustainable product family design.

The procedure of the NSGA-II in Figure 7.5 starts with generating initial population based on encoding chromosome of the sustainable product family. In order to implement the NSGA-II, the chromosome of this research should be created. The chromosome is introduced to support sustainable product family planning. An example of the chromosome is shown in Figure 7.6. The first four genes in the chromosome determine brand-leaders in the markets based on part-worth utility of each module instance. Following design variable is to select a module instance in each module to configure a product. In the first module (M_1), second module instance (m_{12}) is selected in this example. Last part of the chromosome selects module instances for the remanufactured product. For example, a remanufactured module, m_{13} , is selected for the first module of the remanufactured product. Otherwise, new modules are selected for M_2 and M_4 , which are not remanufacturable modules.

Figure 7.5 Working procedure of NSGA [205]

Figure 7.6 Example of a chromosome for sustainable product family design

Then, selection, crossover, and mutation are performed to create new population [206, 207]. The selection is to choose parents for next generation, which is a product configuration, by using tournament selection procedure in this study. However, it is possible to use other selection techniques, such as roulette wheel or stochastic remainder proportional selection. Then the best individual is selected as a parent for creating children. Besides elite children in the current generation that are configurations of products with the best fitness values, the algorithm creates children by crossover and mutation processes. Both processes are essential for the algorithm [207]. The crossover is to form children by extracting the best genes from the parents and then recombining them. On the other hand, the mutation creates children by applying random changes to a single individual. The mutation aims to preserve and generate diversity so that it allows avoiding local minima. Finally, the algorithm results in a final design solution which is a multi-dimensional Pareto front including a set of non-dominating optimal product design variables.

7.4 Case Study

A case study with a family of electric shavers in Figure 7.7 was performed to demonstrate the usefulness of the proposed method. This is because the family of electric shavers has more various modules with different specifications, compared to a family of coffee maker that was used for a case study in the previous chapter. The product architecture of the electric shaver consists of casing with ergonomic grip design, shaving system with blade module and motor, control system, and charging system as shown in Figure 7.8. To enhance usability and meet required performance, there are three products in markets. Electric shaver 1 has simple functions, while electric shavers 2 and 3 have high performance. The shaver 3 has more functions and is more expensive than the shaver 2. Table 7.4 lists all module instances.

Figure 7.7 A product family of AquaTouch Electric Shavers (Philips)⁴

Figure 7.8 Architecture of the electric shavers

Table 7.4 Module instance of the electric shaver family

	Electric shaver 1	Electric shaver 2	Electric shaver 3
Body (M1)	1	2	2
Blade module (M2)	1	2	2
Motor (M3)	1	2	2
Circuit (M4)	1	2	2
Battery (M5)	1	2	3

⁴ <http://dev.philips.com.sg>

Table 7.5 lists part-worth utility of module instance at each market segment. It is assumed that the contribution of product price to the indirect utility function has already been taken into account in the representation of the part-worth utilities for both the company and the competitor products. The part-worth utility represents customer preference of the module instance in market segments. In fourth market segment, part-worth utility represents customer preference when the module instance at the EOL stage is recovered and reused to configure remanufactured products. Remanufactured products have a reasonable price to buy in spite of high performance, compared to new products as shown in Table 7.5. Table 7.6 provides utilities of competitor's product in each market segment. Since the competitor didn't consider remanufactured products, the utility of the competitors in fourth market segment became zero.

Table 7.5 Part-worth utility of a module instance in market segments

		Part-worth utility of Segment 1	Part-worth utility of Segment 2	Part-worth utility of Segment 3	Part-worth utility of Segment 4
M1	M11	3	1	1	1
	M12	2	3	3	3
M2	M21	3	1	1	1
	M22	1	3	3	3
M3	M31	3	2	1	3
	M32	1	3	3	2
M4	M41	3	2	1	1
	M42	1	3	3	3
M5	M51	3	1	1	1
	M52	2	3	2	3
	M53	1	2	3	3

Table 7.6 Utility of competitor's product

	Part-worth utility of Segment 1	Part-worth utility of Segment 2	Part-worth utility of Segment 3	Part-worth utility of Segment 4
Competitor 1	10	10	10	0

According to the number of each module instance which is 2, 2, 2, 2, and 3, the full factorial design would have 48 alternative products ($2 \times 2 \times 2 \times 2 \times 3$). To represent the market segments, four product variants (PV) which are preferred in each market are decided in this case study as follows: PV1 [M11 M21 M31 M41 M51], PV2 [M12 M22 M32 M42 M52], PV3 [M12 M22 M32 M42 M53], and PV4 [M11 M21 M31 M41 M53] based on the electric shaver family. The selected product variants have reflected customer preference from each market segment. It could affect the choice probability and estimate production demands of new and remanufactured products (Q_{new} and Q_{rem}). In this case study, two product variants as brand-leaders were selected to determine the expected production demand. It is assumed that demand (D_i) of products for the first market segment were 40000; 20000 for the second market; 30000 for the third market; and 10000 for the fourth market, respectively.

7.4.1 End-of-life Platform Identification Based on Compatibility Analysis

Then, compatibility between different module instances was analyzed to identify the EOL platform, in terms of function, space, and interface. The compatibility matrix of the electric shaver was developed in Table 7.7. From the viewpoint of sustainability, motor (M3), circuit (M4), and battery (M5) modules were decided as the EOL platform which is able to be shared between products at the EOL stage. These modules are compatible to maintain key functions over product variants in the product family, but have a limitation to perform their full functions. For example, in terms of the circuit (M4), M42 contains battery low and travel lock functions that do not be contained at M41. So, if M42 replaces M41, the function of the M42 could be performed partially to support basic functions. From the compatibility analysis, it was found that M11 is not compatible with M22, and vice versa. Therefore, two constraints were added to produce feasible product configurations: $x_{j11} = x_{j21}$ and $x_{j12} = x_{j22}$.

Table 7.7 Compatibility matrix of module instance of the electric shavers

	M1		M2		M3		M4		M5		
	M11	M12	M21	M22	M31	M32	M41	M42	M51	M52	M53
M11	1	0	1	0	1	1	1	1	1	1	1
M12	0	1	0	1	1	1	1	1	1	1	1
M21	1	0	1	0	1	1	1	1	1	1	1
M22	0	1	0	1	1	1	1	1	1	1	1
M31	1	1	1	1	1	1	1	1	1	1	1
M32	1	1	1	1	1	1	1	1	1	1	1
M41	1	1	1	1	1	1	1	1	1	1	1
M42	1	1	1	1	1	1	1	1	1	1	1
M51	1	1	1	1	1	1	1	1	1	1	1
M52	1	1	1	1	1	1	1	1	1	1	1
M53	1	1	1	1	1	1	1	1	1	1	1

7.4.2 Quality Assessment and Parameter Preparation

For remanufactured products, the quality of a replaceable module (QL) has to be checked to decide whether or not the module can be remanufacturable. If the performance of a module is lower than its threshold or the product recovery cost of the module is higher than cost threshold, the module could not be remanufactured. Namely, if the QL of the module is bigger than one, the module can be remanufacturable for reuse. Accordingly, in this case study, module instance of M1, M3, and M5 modules can be remanufacturable as shown in Table 7.8. It was assumed that reliability of the remanufactured products is required to be 0.9 or above. These thresholds are decided by company's strategies and accumulated data.

Parameters of module instances like price, cost, and environmental impact were assumed in Table 7.9. Environmental impact of new products was determined by Eco indicator 99 [138] over product lifecycle, while environmental impact for remanufacturing was assumed as a half of the environmental impact of new products.

Table 7.8 Quality assessment of module instances

		QL	Performance	Cost_rem	Performance_threshold	Cost_threshold
M1	M11	1.18	1.00	5	0.85	5
	M12	1.96	1.00	3	0.85	5
M2	M21	0.66	0.64	8	0.85	7
	M22	0.85	0.72	7	0.85	7
M3	M31	1.76	1.00	2	0.85	3
	M32	1.76	1.00	2	0.85	3
M4	M41	0.12	0.98	3	0.95	1
	M42	0.47	0.98	3	0.95	2
M5	M51	1.11	1.00	1	0.90	1
	M52	1.11	1.00	1	0.90	1
	M53	1.11	1.00	1	0.90	1

Table 7.9 Parameters of each module instance

		New product			Remanufactured product			
		Price_new	Cost_new	EI_new	Price_rem	Cost_rem	EI_rem	Failure rate_rem
M1	M11	23	10	50	10	5	25	0.120
	M12	45	15	120	17	3	60	0.080
M2	M21	55	30	70	-	-	-	0.002
	M22	65	30	100	-	-	-	0.001
M3	M31	10	5	200	6	2	100	0.008
	M32	15	7	350	7	2	175	0.008
M4	M41	15	7	300	-	-	-	0.010
	M42	30	10	400	-	-	-	0.015
M5	M51	10	5	700	4	1	350	0.030
	M52	15	6	650	7	1	325	0.020
	M53	20	6	600	7	1	300	0.020

7.4.3 Results Based on Four Cases

Four cases were considered to validate the proposed method by investigating whether or not the sustainable product family with considering remanufacturing are more effective for maximizing profits and minimizing environmental impact than the product family with only considering profits.

CASE 1: When a company has priority for maximizing profit only for new products, the proposed method can obtain an optimal product configuration of new products. A genetic algorithm was implemented using Matlab to solve the single objective problem. The results from Case 1 under 51 generations are presented in Figure 7.9 (a). PV2 and PV3 were selected as brand leaders in the markets to maximize customer preference and then the expected demand of new products resulted as 51,539. The optimal product configuration, profits, Q_{new} , and environmental impact were represented in Table 7.10.

CASE 2: When a company develops new product variants and then plan to develop remanufactured products in the EOL stage to maximize profit, the proposed method provides configurations for new products and remanufactured products. The remanufactured product consisted of new modules and remanufactured modules. The remanufactured products were reconfigured after remanufacturing and then testing to use remanufactured modules. The results of Case 2 are shown in Figure 7.9 (b). The PV2 and PV3 were selected as brand-leaders in this case. Accordingly, new and remanufactured products were configured to maximize the profit of new products and remanufactured products as shown in Table 7.10. The product configurations, profits, expected production quantity (Q_{new} and Q_{rem}), and environmental impact were presented in Table 7.10.

(a)

(b)

Figure 7.9 Best profit value for (a) Case 1 and (b)Case 2

Table 7.10 Results of product configuration for maximizing profits in Case 1 and Case 2

		Case 1	Case 2
		(Only profit for new)	(Profits for new and remanufactured)
Brand-leader in market		PV2 and PV3	PV2 and PV3
New product	Product configuration	[M12 M22 M32 M42 M52]	[M12 M22 M32 M42 M53]
	Profit	5,257,000	5,400,500
	Q_{new}	51,539	50,472
	EI (mPt)	83,494,000	79,241,000
Remanufactured product	Product configuration	-	[M11* M21 M32* M41 M53*]
	Profit	-	489,980
	Q_{rem}	-	10,000
	EI (mPt)	-	8,560,300
Total Q		51,539	60,472
Total profit		5,257,000	5,890,480
Total EI (mPt)		83,494,000	87,801,300

*Remanufactured module

CASE 3: Based on Case 2, the environmental impact was additionally considered as the second objective. NSGA-II algorithm using Matlab was applied to solve the optimization problem. The Pareto front was obtained as shown in Figure 7.10 (a). The feasible design solution space could be decided to determine the trade-off between profit and environmental impact by designer's preference and company's strategies. In the feasible design solution space, new and remanufactured product variants were determined to maximize profits and minimize the environmental impact when PV3 and PV4 were selected in the markets as shown in Table 7.11.

CASE 4: In Case 3, new product configuration was developed for new market, while remanufactured product was planned to reconfigure usable modules/components after remanufacturing at the EOL stage. Unlike the Case 3, Case 4 was to develop a sustainable product family that considered new and remanufactured product configurations simultaneously at the early product design stage. In other words, the configuration of new products is developed by considering the profit and environmental

impact of remanufactured products in advance. Therefore, the Case 4 with the optimization problem was modelled to identify the trade-off between the profit and the environmental impact by setting $y_{jkl}=x_{jkl}$. The Pareto front was obtained as shown in Figure 7.10 (b). Among points that represent product family configurations at Pareto front, the point of Pareto front at 40,000,000 mPt of the environmental impact for Cases 3 and 4 is used to select a sustainable product family configuration as a selection reference.

As a limitation, although binary variables were used to select module instances in this study, NSGA-II resulted in Pareto front with continuous values. Accordingly, the continuous values of neighbor points were converted to 0 or 1 for selecting module instances. When the continuous values of module instances in k th module were the maximum value among them, the values were converted to 1. Otherwise, the value was 0. In this case study, the converted values of the neighbor points were converged towards a product family configuration. Finally, by applying the converted values to the object functions, final results of Cases 3 and 4 were determined as shown in Table 7.11.

(a)

(b)

Figure 7.10 Pareto Front of (a) Case 3 and (b) Case 4 (Number of Pareto front: 137, Number of generations: 100)

Table 7.11 A result of Pareto front for Case 3 and Case 4

		Case 3	Case 4
Brand-leader in markets		PV3 and PV4	PV1 and PV2
New product	Product configuration	[M12 M22 M31 M42 M53]	[M12 M22 M32 M42 M52]
	Profit	4,307,600	6,167,900
	Q_{new}	41,419	60,167
	EI	58,815,000	88,863,000
Remanufactured product	Product configuration	[M11* M21 M32* M42 M52*]	-
	Profit	610,000	-
	Q_{rem}	10,000	-
	EI	9,700,000	-
Total Q		51,419	60,167
Total profit		4,917,600	6,167,900
Total EI		68,515,000	88,863,000

7.5 Discussion

Since the expected production demand (Q) of each market segment is different according to selected product variants in the market, it is difficult to compare each case. So, the expected production demand of each case was equalized by multiplying a normalizing factor that is a ratio of the production demand of each Case and the production demand of Case 4 as shown in Table 7.12 and Figure 7.11.

Table 7.12 Normalizing results of each case

		Case 1	Case 2	Case 3	Case 4
Original value	Total production	51,539	60,472	51,419	60,167
	Total Profit	5,257,000	5,890,480	4,917,600	6,167,900
	Total EI	83,494,000	87,801,300	68,515,000	88,863,000
Normalized value	Normalizing factor	1.17	0.99	1.17	1.00
	Total production	60,167	60,167	60,167	60,167
	Total Profit	6,137,060	5,860,770	5,754,239	6,167,900
	Total EI	97,471,497	87,358,460	80,171,571	88,863,000

Figure 7.11 Design solution of each case and thresholds for identifying sustainable product variant

Case 1 had achieved a high profit with \$6,137,060 because its objective was only to maximize profit. However, since Case 1 did not consider environmental impact, the environmental impact of Case 1 had the highest value. Cases 2 resulted in new and remanufactured product configurations. However, Case 2 aimed to maximize only the profit without considering the environmental impact. Total profit of Case 2 was about 5% lower than one of Case 1, while the total environmental impact of Case 2 was about 10% lower than one of Case 1.

Case 3 had considered the environmental impact, and resulted in new and remanufactured product configurations. Compared to Case 2, total profit of Case 3 was \$5,754,239 which is about 2% lower than one of Case 2. However, Case 3 had reduced about 9% environmental impact rather than Case 2. Also, Case 3 provided the lowest environmental impact among these Cases. Case 4 resulted in the highest profit and the environmental impact of Case 4 was 10% higher than Case 3.

Through these results, company strategies and environmental regulations are required for decision making. If environment regulations were restricted to the environmental impact below 90 million mPt (milli-point), product family configuration in Cases 2, 3 and 4 could be selected as a sustainable product family as shown in Figure 7.11 and Table 7.13. Additionally, when the expected profit of a company was more than 6 million dollars, the product variants from Case 4 could satisfy both the environmental regulations and the expected profit threshold. In that sense, product family configurations of Case 4 were selected as the sustainable product family configuration as shown in Table 7.14.

Table 7.13 Sustainable product family configuration and platform based on only environmental regulation

Product family	M1	M2	M3	M4	M5	Remarks
Product variant for market 1	M11	M21	M31	M41	M51	Low-end product
Product variant for market 2	M12	M22	M32	M42	M52	Middle-level product
Product variant for market 3	M12	M22	M32	M42	M53	High-end product
Product variant for market 4	M11	M21	M31	M41	M53	Product with Less environmental impact
New product	M12	M22	M32	M42	M53	From Case 2
New product	M12	M22	M31	M42	M53	From Case 3
Remanufactured product	M11*	M21	M32*	M41	M53*	From Case 2
Remanufactured product	M11*	M21	M32*	M42	M52*	From Case 3
Sustainable product	M12	M22	M32	M42	M52	From Case 4
EOL platform	No	No	Yes	Yes	Yes	

*Remanufactured module

Table 7.14 Sustainable product family in this case study based on environmental regulation and profit threshold

Sustainable product family	M1	M2	M3	M4	M5	Remarks
Product variant for market 1	M11	M21	M31	M41	M51	Low-end product
Product variant for market 2	M12	M22	M32	M42	M52	Middle-level product
Sustainable product	M12	M22	M32	M42	M52	From Case 4
EOL platform	No	No	Yes	Yes	Yes	

To provide the sustainable product family, the EOL platform was determined with three modules (M3, M4, M5) including module instances. Three modules (M1, M3, M5) were decided as remanufacturable modules. From the case study, the M1 which was not an EOL platform but remanufacturable module was restrictedly reused. This was because a module instance of M1 was decided based on a module instance of M2. Therefore, the EOL platform that is compatible and remanufacturable was M3 and M5 in this case study, and provided a chance to share remanufactured modules between products to prolong product lifecycle. In this research, the EOL platform was a foundation of developing the configuration of the sustainable product family and gave flexibility for a product recovery strategy.

Additionally, in order to understand how assumptions, such as utilities of competitor's products, profit, and environmental impact for remanufacturing, will affect final results, a sensitivity analysis was performed based on Case 4. Accordingly, Pareto front of Case 4 was used as a basis of the sensitivity analysis when the utilities were 10; the profit was not increased; and when the environmental impact for remanufacturing was equal to a half of the environmental impact of new products. In terms of the utilities of competitor's product, the utilities can affect the final output. As shown in Figure 7.12, Pareto front was moved to the left when the utilities of the competitors' product were increasing. The tendency of Pareto front reflected that profits were declined when competitor's products were more preferable.

Figure 7.12 Results of sensitivity analysis according to a change to utility of a competitor

In terms of the profit and the environmental impact, results of the sensitivity analysis were as follows. As the profit was increased by 10%, 20%, and 30%, Pareto front moved the right by reflecting the profit increment as shown in Figure 7.13. Since the gap of Pareto front between ‘no increase’ and ‘30% increase’ was quite wide, the final output would be affected by the profit as an input. Also, the environmental impact for remanufacturing was changed to one-quarter and three-quarters of the environmental impact of new products. Figure 7.14 shows a comparison of Pareto front as the result of the sensitivity analysis. The change of the environmental impact for remanufacturing affected the result of this study.

Figure 7.13 Results of sensitivity analysis according to a change to profit

Figure 7.14 Results of sensitivity analysis according to a change to the environmental impact for remanufacturing

7.6 Summary and Preview

As sustainability has rightfully received a lot of attention, product design has become more important to consider sustainability at an early product design stage. This study

proposed a method to identify a sustainable product family configuration by integrating sustainability performances and an EOL platform strategy. A multiobjective design optimization model was constructed to reflect the sustainability performances. A sustainable product family design was introduced to enhance profits, reduce environmental impact, and prolong product lifecycle by reusing remanufactured modules. The EOL platform strategy was also introduced to share remanufactured modules among products in a product family by analyzing compatibility in terms of spatial, functional, and interface restrictions. Then, the multiobjective design optimization for determining the configuration of the sustainable product family was performed to trade profits off against environmental impact. Therefore, this proposed method contributes to showing that the sustainable product family can reduce environmental impact while keeping profits. A case study was performed to demonstrate the usefulness of the proposed method. The sensitivity analysis was performed to understand how assumptions in the case study affected the results.

The limitation of this research is that Pareto front provides solutions with continuous values instead of binary values. Therefore, the continuous values were converted to the binary values for selecting module instances. Since this converting process may cause uncertain errors, the proposed method will be improved to resolve this issue. Also, this study does not consider time-varying advantage of the sustainable product family. This study will be extended to show how the product family design with an EOL platform strategy promotes environmentally sustainable growth over the product lifespan. Future work will focus on integrating this study, which is a company perspective method, into a consumer perspective method. It will provide what kinds of sustainability aspects are important for consumers and then how the aspects affect sustainable product family design.

The next and final chapter presents a summary of achievements, contributions, and limitations of this study. Recommendations and future research direction along with the discussion of the limitations are provided.

Chapter 8. Conclusion

In this dissertation, the Sustainable Product Family Design Method (SPFDM) has been developed, presented, and evaluated to support product family design with concerning sustainability, especially, environmental impact and a product recovery strategy over product lifecycle. Chapter 8.1 reviews the research objectives and the proposed methods. The resulting contributions and limitations of this dissertation are summarized in Chapter 8.2. Future work is discussed in Chapter 8.3.

8.1 Research Summary

As public awareness and environmental regulation of governments for sustainability are getting stringent nowadays, manufacturers should make products more sustainable by integrating the environmental regulation and product lifecycle into product design. This dissertation discusses a design methodology for a sustainable product family. The most important consideration for achieving the sustainable product is the development and implementation of product architecture design, which is fundamental level design in the early product design stage. Our first principle hypothesis is that a product architecture plays a predominant role in determining characteristics of assembly, disassembly, maintenance, upgrade, and product lifecycle. Accordingly, this research has mainly focused on product family design based on modular architecture improvement.

The primary objective embodied in the SPFDM is to manage and determine a sustainable product family by applying environmental, economic, and social performances into product family design. The SPFDM consists of analyzing product design information, assessing the product design, developing a new concept of the modular architecture for product recovery, and determining a sustainable/EOL platform and a sustainable product family.

In order to apply sustainability performances into product design, in Chapter 4, a product disassembly complexity is investigated to measure the difficulty of disassembly quantitatively by modifying entropy theory. The complexity of product design is established based on information from design for disassembly, such as the number of constituents, component design, and interface types. In order to measure disassembly difficulty in terms of component design, four main attributes are considered: weight, size, symmetry, grasping and manipulations based on the design for assembly and disassembly. For interface design, three attributes are applied: mechanical unfastening process, non-mechanical unfastening process, and tools required with low/high intensity. When designers develop components and interfaces in a product without considering disassembly operations and reducing the number of constituents, the product disassembly complexity has been increased. It has been evaluated by two case studies with families of electric shavers and coffee makers.

By using the information on the product disassembly complexity in Chapter 4 as one of the sustainable modular drivers, eco-modular architecture design and its modularity assessment method are introduced in Chapter 5. The sustainable modular drivers that consist of interface complexity/product disassembly complexity, material similarity, and lifespan similarity, are introduced to support the development of the eco-modular architecture. Markov Cluster Algorithm is applied to identify the eco-modular architecture with maintaining functional and physical dependencies of components in a product. Then, a novel modularity assessment method is introduced to assess whether the modular architecture is configured by reflecting designers' intent or not. Finally, the best eco-modular architecture is selected by the proposed modularity assessment method. The eco-modular architecture design and its modularity assessment method are evaluated by a case study with a coffee maker.

The eco-modular architecture in Chapter 5 has been determined to support a single product in a product family. To extend the eco-modular architecture to a product family, a sustainable platform is introduced in Chapter 6. Unlike the current platform

that focuses only on commonality, the sustainable platform has considered not only commonality but also sustainability value and risk. The sustainable platform strategy focuses on new product family production with considering the sustainability performance. When it comes to assessing the sustainability value, the information on the sustainability is acquired from sustainability indicators that consist of environmental indicator, e.g., greenhouse gases, economic indicator, e.g., lifecycle cost, and social indicator, e.g., toxic materials in workplaces. Since the scope and unit of the sustainability indicators are different, grey relational analysis in multi attribute decision making approaches is utilized to normalize and aggregate the information from different indicators into the total sustainability value. Additionally, designers can use the total sustainability value to compare more than two products for benchmarking sustainable products. In order to quantify the robustness of components against the product redesign, the risk of components is calculated by a product of conditional probability and redesign cost of a component. To estimate the conditional probability of the components, Bayesian network is used to update probability distribution of unobserved variables when components in a product family are redesigned. Accordingly, components with high risk mean that the components have high possibility to be redesigned when propagating design changes from other components. Designers can check which components are stable or risky to be redesigned when redesigning a component for enhancing sustainability. After getting information of components like commonality, sustainability value, and risk to be redesigned, a fuzzy inference system is used to decide the sustainable platform that has high commonality, high sustainability value, and low risk. A case study with a family of coffee makers is performed to compare sustainability among the coffee makers and determine the sustainable platform for the coffee makers.

By applying the eco-modular architecture in Chapter 5 and the sustainable platform in Chapter 6, a sustainable product family is configured in Chapter 7. The sustainable platform should be analyzed to know whether or not the platform is compatible or not in terms of physical size, function, and interface. Accordingly, a scope

of the sustainable platform is extended to a platform for the end-of-life stage with considering remanufacturing. Then, the end-of-life platform is determined by analyzing compatibilities between modules for enhancing the feasibility of remanufactured products in Chapter 7. In Chapter 7, sustainable product family configuration has been determined to enhance profits and environmental performance by considering manufacturing stage and EOL (remanufacturing) stage. The configuration of the sustainable product family has stood on the basis of the EOL platform strategy and the eco-modular architecture from previous chapters. In order to configure the sustainable product family, a multiobjective design optimization model is introduced to maximize profits and minimize environmental impact from manufacturing and remanufacturing. The design information, such as profits and environmental impact from manufacturing and remanufacturing, are considered, and mathematical models for acquiring quantitative measures of the design information are developed to interact with the multiobjective design optimization model. Since the expected production demand for new and remanufactured products is closely related to the profits and environmental impacts, the expected production demand is estimated by a multinomial logit model based on customer preference. Finally, the sustainable product family is determined by a trade-off between maximizing profits and minimizing environmental impact. A case study with a family of electric shavers is performed to evaluate the proposed method.

8.2 Contributions and Limitations of the Research

The main contribution of this dissertation is to address a current product modular design problem and then provides the Sustainable Product Family Design Methodology (SPFDM) to resolve the design problem. The main result from the methodology is to identify the new concept of product architecture, a platform, and a product family from the viewpoint of the product lifecycle. The specific contributions of this dissertation are summarized as follows:

- Develop the assessment method of the product disassembly complexity to know difficulty of disassembly for product recovery strategy, see Chapter 4
- Develop the new concept of modular product architecture to enhance a product recovery strategy, especially reusability and recyclability, without further disassembly into components or materials, see Chapter 5
- Introduce the new method of modularity assessment for evaluating modular product architectures and selecting the eco-modular product architecture, see Chapter 5
- Identify a sustainable platform, which is the extended platform of current design, by integrating sustainability value, risk in redesigning a product, and commonality, see Chapter 6
 - Aggregate and compare degree of sustainability that is from environmental, economic, and social indicators by using a multi-attribute decision making approach, see Chapter 6.2.3
 - Predict the robustness of components and unexpected change propagation when redesigning a component in a product based on Bayesian network, see Chapter 6.4
- Identify a sustainable product family based on the EOL platform, customer preference, profit, and environmental impact by proposing a multi-objective design optimization model, see Chapter 7

The contributions for product design provide foundations for modelling the link between product design and sustainability which is environmental, economic, and social performances. Accordingly, the new concept of product design methods is developed to support how to evaluate which design is better than others and why in terms of product architecture design, and then apply the evaluated sustainability information into product family design. This methodology provides not only a fundamental design approach to

consider sustainability in the product architecture level, but also a starting point of extending eco-design in the single product level to the eco-design in a product family level.

This research in the dissertation has evaluated with various case studies and has significances from both research and industrial perspectives. However, some improvement can be taken into account.

(1) Design information related to sustainability. Collecting design information on sustainability is critical to redesign modular product architecture for sustainability. In this dissertation, product analysis is performed through dissection of existing products. Although design information in the bill of material, such as dependency between components, material types, manufacturing process, and so on, can be collected, product characteristics related to sustainability like product lifespan and environmental impact are difficult to collect from the product analysis. Therefore, in this research, the sustainability-related information is assumed or estimated based on conventional methods. The quality of the data can influence achieving goals of sustainable product family design. In this sense, when considering various and correct information on sustainability in product design, final products from the SPFDM are more closed to target design which well reflects designers' intent. Accordingly, a methodology is needed to estimate design information related sustainability from trends of accumulated design data.

(2) Product assessment approaches for decision-making from the viewpoint of sustainability. Since a few studies focused on sustainable product family design, there are not many tools to assess sustainable design. Accordingly, three assessment methods are developed in this research as follows: product disassembly complexity in Chapter 4; modularity for the end-of-life stage in Chapter 5; and sustainability value aggregation method in Chapter 6. However, these methods have developed to support mainly the end-of-life stage of a product. The results from the assessment methods help designers decide which product architectures are suitable for companies' product recovery

strategies, especially disassemblability, reusability, and recyclability. However, benefits of the sustainable product should be assessed over the product lifecycle rather than discrete assessments at the sudden point like current product assessment, e.g., profits and costs of a product. Therefore, the proposed assessment methods are needed to be extended to capture various stages of product lifecycle.

Through the research has some limitations, these limitations provide an avenue for future improvements. Recommendations and future work for sustainable product family design are discussed in the next sub-chapter.

8.3 Recommendations and Future Research Direction

Although the SPFDM has focused on product design mainly for the end-of-life stage of the product lifecycle, it should be extended to integrate other lifecycle stages for enhancing sustainability. More holistic approach should be investigated to evaluate, redesign, and substantiate sustainable product family design for maximizing profits and environmental performance over the product lifecycle. In order to achieve this capability, the recommendations and future work are highlighted as follows.

(1) Product Architecture Evaluation: In Chapters 4 and 5, product evaluations have been conducted towards sustainable products. While the evaluation validates the SPFDM and enhances the sustainable capability of product architectures, especially disassemblability, reusability, and recyclability, it does not focus on evaluation from the manufacturing perspective. Thus, more approaches need to be developed to perform an evaluation on both manufacturing and sustainability. These approaches should include the ability to optimize product architecture for manufacturing and plan which modules and how many modules are necessary for a sustainable product family as well as a sustainable platform.

(2) Evaluation of Eco-modular Product Architecture and Sustainable Platform Design: Eco-modular product architecture in Chapter 5 and a sustainable platform in

Chapter 6 have been developed and theoretically evaluated based on current products without suggesting how to redesign current components/modules design for sustainable products. For identification of a sustainable product platform, product redesign and change propagation from a design change of a component were considered. However, future efforts should be placed on the track of product redesign and cost modelling for planning a sustainable product family by improving Bayesian network. It will provide detailed product design plan from current product design to sustainable design with predicting unexpected design changes and costs.

(3) *Market Niche for Sustainable Products*: Customer preference is applied to determine the demands of remanufactured products, and then the optimal remanufactured product configurations are determined in Chapter 7. However, it does not research how to determine market segmentation for sustainable products. To support the method in Chapter 7, future efforts should possess the ability to identify market segmentation for sustainable products with considering market uncertainty.

(4) *Time-based Methodology for Proving Benefits of a Sustainable Product Family*: Conventional product design has mainly focused on manufacturing and been assessed from the viewpoint of manufacturing. However, sustainable product design has been built on the basis of the product lifecycle. To reflect the product lifecycle, this study tried to apply design information over the product lifecycle into product design. For example, environmental impact in Chapters 6 and 7 is estimated from raw material stage to disposal stages. Also, profits are modelled along manufacturing and remanufacturing processes in Chapter 7. However, to concretely assess the benefits of a sustainable product family over the product lifecycle, time-based methodological and theoretical approaches should be developed. The time-based methods will help predict product lifespan, profits, costs, and environmental impact over the product lifecycle. According to the predicted information, decision makers will decide which components or modules are more profitable and when the components should be replaced to maximize product lifespan, profit, and environmental performance.

(5) New Technology Adoption for Sustainable Product Family: Current product design methods have been developed to enhance conventional production system rather than applying new technology into product design. However, as additive manufacturing technology is getting developed for maximizing freedom of product design, designers can have more opportunities to produce more complex products while reducing materials and energy usage. Therefore, incorporating key design information related to product lifecycle and additive manufacturing is needed to study how new technology has a great impact on product design and how product design will become more sustainable.

Publications

S. Kim and S. K. Moon, "Multiobjective Design Optimization for Identifying Sustainable Product Family Configuration," *Journal of Engineering Design (Under review)*

S. Kim and S. K. Moon, "Sustainable Platform Identification for Product Family Design," *Journal of Cleaner Production*, vol. 143, p. 567-581, 2017.

S. Kim and S. K. Moon, "Eco-modular product architecture identification and assessment for product recovery," *Journal of Intelligent Manufacturing*, pp. 1-21, 2016, DOI 10.1007/s10845-016-1253-7.

S. Kim, S. K. Moon, S. M. Jeon, and H. S. Oh, "A disassembly complexity assessment method for sustainable product design," in 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bali, Indonesia, 2016, pp. 1468-1472.

S. Kim and S. K. Moon, "Assessing and Generating Modules for Product Recovery," presented at the Proceedings of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, DETC2015-47130, Boston, Massachusetts, USA, 2015.

S. Kim, J. W. Baek, S. K. Moon, and S. M. Jeon, "A New Approach for Product Design by Integrating Assembly and Disassembly Sequence Structure Planning," in Proceedings of the 18th Asia Pacific Symposium on Intelligent and Evolutionary Systems. vol. 1, ed Switzerland: Springer, 2015, pp. 247-257.

S. Kim, S. K. Moon, H. S. Oh, T. Park, H. Choi, and H. Son, "A framework to identify sustainability indicators for product design," in Industrial Engineering and Engineering Management (IEEM), 2014 IEEE International Conference on, Selangor, Malaysia, 2014, pp. 44-48.

S. Y. Kim, S. K. Moon, H. S. Oh, T. Park, G. Kyung, and K. J. Park, "Change propagation analysis for sustainability in product design," in Industrial Engineering and

Engineering Management (IEEM), 2013 IEEE International Conference on, Bangkok, Thailand, 2013, pp. 872-876.

S. K. Moon, H. S. Oh, and S. Kim, "A Product-Service System Model for Identifying Design Factors," in ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Portland, Oregon, USA, 2013, pp. V03BT03A041-V03BT03A041.

S. K. Moon, H. S. Oh, S. Kim, and J. Hwang, "A product-service system design framework using objective-oriented concepts and blueprint," presented at the Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 4: Product, Service and Systems Design, Seoul, Korea, 2013.

Bibliography

- [1] K. Ramani, D. Ramanujan, W. Z. Bernstein, F. Zhao, J. Sutherland, C. Handwerker, *et al.*, "Integrated sustainable life cycle design: A review," *Journal of Mechanical Design*, vol. 132(9), p. 091004, 2010.
- [2] G. Howarth and M. Hadfield, "A sustainable product design model," *Materials & Design*, vol. 27(10), pp. 1128-1133, 2006.
- [3] M. A. Ilgin and S. M. Gupta, "Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art," *Journal of Environmental Management*, vol. 91(3), pp. 563-591, 2010.
- [4] Department of the Environment in Australian Government. *Measuring Sustainability program* <<http://www.environment.gov.au/topics/sustainable-communities>>. Available: <http://www.environment.gov.au/topics/sustainable-communities>
- [5] United States Environmental Protection Agency. *Sustainability*. Available: <http://www.epa.gov/sustainability/>
- [6] A.-R. Mohamed, "Effects of active learning variants on student performance and learning perceptions," 2008.
- [7] M. J. Kwak, Y. S. Hong, and N. W. Cho, "Eco-architecture analysis for end-of-life decision making," *International Journal of Production Research*, vol. 47(22), pp. 6233-6259, 2009.
- [8] M. Kutz, *Environmentally conscious mechanical design* vol. 1. Hoboken, New Jersey: John Wiley & Sons, Inc., 2007.
- [9] S. Kim and S. K. Moon, "Assessing and Generating Modules for Product Recovery," presented at the Proceedings of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, DETC2015-47130, Boston, Massachusetts, USA, 2015.
- [10] C. Sherwin and T. Bhamra, "Beyond engineering: ecodesign as a proactive approach to product innovation," in *Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. EcoDesign'99: First International Symposium On*, 1999, pp. 41-46.

- [11] M. Kwak and H. Kim, "Market Positioning of Remanufactured Products With Optimal Planning for Part Upgrades," *Journal of Mechanical Design*, vol. 135p. 011007, 2013.
- [12] S. W. Kang, C. Sane, N. Vasudevan, and C. S. Tucker, "Product Resynthesis: Knowledge Discovery of the Value of End-of-Life Assemblies and Subassemblies," *Journal of Mechanical Design*, vol. 136(1), p. 011004, 2014.
- [13] G. Da Silveira, D. Borenstein, and F. S. Fogliatto, "Mass customization: Literature review and research directions," *International Journal of Production Economics*, vol. 72(1), pp. 1-13, 2001.
- [14] K. T. Ulrich and S. D. Eppinger, *Product design and development* 5ed. New York: McGraw-Hill, 2012.
- [15] F. Borjesson and K. Hölttä-Otto, "A module generation algorithm for product architecture based on component interactions and strategic drivers," *Research in Engineering Design*, vol. 25(1), pp. 31-51, 2014.
- [16] Z.-H. You and S. Smith, "A multi-objective modular design method for creating highly distinct independent modules," *Research in Engineering Design*, pp. 1-13, 2016.
- [17] S.-W. Hsiao, Y.-C. Ko, C.-H. Lo, and S.-H. Chen, "An ISM, DEI, and ANP based approach for product family development," *Advanced Engineering Informatics*, vol. 27(1), pp. 131-148, 2013.
- [18] W.-H. Chung, G. E. Okudan Kremer, and R. A. Wysk, "A Modular design approach to improve product life cycle performance based on the optimization of a closed-loop supply chain," *Journal of Mechanical Design*, vol. 136(2), pp. 021001-021001, 2014.
- [19] N. Chiriac, K. Hölttä-Otto, D. Lysy, and E. S. Suh, "Level of modularity and different levels of system granularity," *Journal of Mechanical Design*, vol. 133(10), p. 101007, 2011.
- [20] T. W. Simpson, "Product platform design and customization: Status and promise," *Ai Edam-Artificial Intelligence for Engineering Design Analysis and Manufacturing*, vol. 18(1), pp. 3-20, 2004.
- [21] M. Kwak, "Green profit design for lifecycle," Doctor of Philosophy Dissertation, Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA, 2012.
- [22] M. Lindahl, E. Sundin, J. Östlin, and M. Björkman, "Concepts and definitions for product recovery Analysis and clarification of the

terminology used in academia and industry," in *Innovation in Life Cycle Engineering and Sustainable Development*, D. Brissaud, S. Tichkewitch, and P. Zwolinski, Eds., ed Netherlands: Springer, 2006, pp. 123-138.

- [23] M. Thierry, M. Salomon, J. van Nunen, and L. van Wassenhove, "Strategic Issues in Product Recovery Management," *California Management Review*, vol. 37(2), pp. 114-135, 1995.
- [24] H. R. Krikke, A. van Harten, and P. C. Schuur, "On a medium term product recovery and disposal strategy for durable assembly products," *International Journal of Production Research*, vol. 36(1), pp. 111-140, 1998.
- [25] A. Gungor and S. M. Gupta, "Issues in environmentally conscious manufacturing and product recovery: a survey," *Computers & Industrial Engineering*, vol. 36(4), pp. 811-853, 1999.
- [26] S. K. Fixson, "Product architecture assessment: a tool to link product, process, and supply chain design decisions," *Journal of Operations Management*, vol. 23(3-4), pp. 345-369, 2005.
- [27] A. Griffin, "Modeling and measuring product development cycle time across industries," *Journal of Engineering and Technology Management*, vol. 14(1), pp. 1-24, 1997.
- [28] T. Kaski and J. Heikkila, "Measuring product structures to improve demand-supply chain efficiency," *International Journal of Technology Management*, vol. 23(6), pp. 578-598, 2002.
- [29] P. J. Newcomb, B. Bras, and D. W. Rosen, "Implications of modularity on product design for the life cycle," *Journal of Mechanical Design*, vol. 120(3), pp. 483-490, 1998.
- [30] K. Ishii, C. F. Eubanks, and P. Di Marco, "Design for product retirement and material life-cycle," *Materials & Design*, vol. 15(4), pp. 225-233, 1994.
- [31] T. W. Simpson, J. R. A. Maier, and F. Mistree, "Product platform design: method and application," *Research in Engineering Design-Theory Applications and Concurrent Engineering*, vol. 13(1), pp. 2-22, 2001.
- [32] M. H. Meyer and A. P. Lehnerd, *The power of product platforms: Building value and cost leadership*. New York: The Free Press, 1997.
- [33] Y. Umeda, S. Fukushima, K. Tonoike, and S. Kondoh, "Product modularity for life cycle design," *CIRP Annals - Manufacturing Technology*, vol. 57(1), pp. 13-16, 2008.

- [34] K. N. Otto and K. L. Wood, *Product design : techniques in reverse engineering and new product development*: Upper Saddle River, NJ : Prentice Hall., 2001.
- [35] Q. Yang, S. Yu, and D. Jiang, "A modular method of developing an eco-product family considering the reusability and recyclability of customer products," *Journal of Cleaner Production*, vol. 64(0), pp. 254-265, 2014.
- [36] J. Fiksel, *Design for Environment: A Guide to Sustainable Product Development*. New York: McGraw Hill, 2009.
- [37] D. T. Allen and D. R. Shonnard, *Sustainable engineering : concepts, design, and case studies*. Upper Saddle River, NJ, USA: Prentice Hall, 2011.
- [38] B. Lu, J. Zhang, D. Xue, and P. Gu, "Systematic Lifecycle Design for Sustainable Product Development," *Concurrent Engineering*, vol. 19(4), pp. 307-324, 2011.
- [39] J. Jeswiet and M. Hauschild, "EcoDesign and future environmental impacts," *Materials & Design*, vol. 26(7), pp. 629-634, 2005.
- [40] V. Lofthouse, "Ecodesign tools for designers: defining the requirements," *Journal of Cleaner Production*, vol. 14(15–16), pp. 1386-1395, 2006.
- [41] P. Deutz, M. McGuire, and G. Neighbour, "Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers," *Journal of Cleaner Production*, vol. 39(0), pp. 117-128, 2013.
- [42] S. Devanathan, D. Ramanujan, W. Z. Bernstein, F. Zhao, and K. Ramani, "Integration of sustainability into early design through the function impact matrix," *Journal of Mechanical Design*, vol. 132(8), p. 081004, 2010.
- [43] A. Mayyas, A. Qattawi, M. Omar, and D. Shan, "Design for sustainability in automotive industry: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 16(4), pp. 1845-1862, 2012.
- [44] G. H. Brundtland, *Report of the World Commission on environment and development: "our common future."*: United Nations, 1987.
- [45] J.-R. Chou, "An ARIZ-based life cycle engineering model for eco-design," *Journal of Cleaner Production*, vol. 66(0), pp. 210-223, 2014.

- [46] V. Poudalet, J.-A. Chayer, M. Margni, R. Pellerin, and R. Samson, "A process-based approach to operationalize life cycle assessment through the development of an eco-design decision-support system," *Journal of Cleaner Production*, vol. 33(0), pp. 192-201, 2012.
- [47] P. Knight and J. O. Jenkins, "Adopting and applying eco-design techniques: a practitioners perspective," *Journal of Cleaner Production*, vol. 17(5), pp. 549-558, 2009.
- [48] D. Chang, C. K. M. Lee, and C.-H. Chen, "Review of life cycle assessment towards sustainable product development," *Journal of Cleaner Production*, vol. 83pp. 48-60, 2014.
- [49] ISO (International Organization for Standardization), "Environmental management-Life cycle assessment-Requirements and guidelines," in *BS EN ISO 14044:2006*, ed: British Standard, 2006.
- [50] M. Inoue, K. Lindow, R. Stark, K. Tanaka, Y.-E. Nahm, and H. Ishikawa, "Decision-making support for sustainable product creation," *Advanced Engineering Informatics*, vol. 26(4), pp. 782-792, 2012.
- [51] T. Sakao, "A QFD-centred design methodology for environmentally conscious product design," *International Journal of Production Research*, vol. 45(18-19), pp. 4143-4162, 2007.
- [52] A. J. D. Lambert, "Determining optimum disassembly sequences in electronic equipment," *Computers & Industrial Engineering*, vol. 43(3), pp. 553-575, 2002.
- [53] A. J. D. Lambert, "Disassembly sequencing: A survey," *International Journal of Production Research*, vol. 41(16), pp. 3721-3759, 2003.
- [54] A. J. D. Lambert, "Linear programming in disassembly/clustering sequence generation," *Computers and Industrial Engineering*, vol. 36(4), pp. 723-738, 1999.
- [55] S. Behdad, L. P. Berg, D. Thurston, and J. Vance, "Leveraging virtual reality experiences with mixed-integer nonlinear programming visualization of disassembly sequence planning under uncertainty," *Journal of Mechanical Design*, vol. 136(4), p. 041005, 2014.
- [56] A. GÜngÖr and S. M. Gupta, "Disassembly sequence plan generation using a branch-and-bound algorithm," *International Journal of Production Research*, vol. 39(3), pp. 481-509, 2001.

- [57] S. Smith and W.-H. Chen, "Rule-based recursive selective disassembly sequence planning for green design," *Advanced Engineering Informatics*, vol. 25(1), pp. 77-87, 2011.
- [58] J. Sung and B. Jeong, "A heuristic for disassembly planning in remanufacturing system," *ScientificWorldJournal*, vol. 2014p. 949527, 2014.
- [59] Y.-J. Tseng, F.-Y. Yu, and F.-Y. Huang, "A green assembly sequence planning model with a closed-loop assembly and disassembly sequence planning using a particle swarm optimization method," *The International Journal of Advanced Manufacturing Technology*, vol. 57(9-12), pp. 1183-1197, 2011.
- [60] J. L. Rickli and J. A. Camelio, "Multi-objective partial disassembly optimization based on sequence feasibility," *Journal of Manufacturing Systems*, vol. 32(1), pp. 281-293, 2013.
- [61] S. Kim, J. W. Baek, S. K. Moon, and S. M. Jeon, "A New Approach for Product Design by Integrating Assembly and Disassembly Sequence Structure Planning," in *Proceedings of the 18th Asia Pacific Symposium on Intelligent and Evolutionary Systems*. vol. 1, ed Switzerland: Springer, 2015, pp. 247-257.
- [62] S. D. Eppinger and K. T. Ulrich, *Product design and development*: New York: McGraw-Hill, 2003.
- [63] A. Jose and M. Tollenaere, "Modular and platform methods for product family design: literature analysis," *Journal of Intelligent Manufacturing*, vol. 16(3), pp. 371-390, 2005.
- [64] K. T. Ulrich, "The role of product architecture in the manufacturing firm," *Research Policy*, vol. 24(3), pp. 419-440, 1995.
- [65] T.-L. Yu, A. Yassine, and D. Goldberg, "An information theoretic method for developing modular architectures using genetic algorithms," *Research in Engineering Design*, vol. 18(2), pp. 91-109, 2007.
- [66] J. Yan, C. Feng, and K. Cheng, "Sustainability-oriented product modular design using kernel-based fuzzy c-means clustering and genetic algorithm," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 226(10), pp. 1635-1647, 2012.
- [67] R. Helmer, A. Yassine, and C. Meier, "Systematic module and interface definition using component design structure matrix," *Journal of Engineering Design*, vol. 21(6), pp. 647-675, 2010.

- [68] T. U. Pimmler and S. D. Eppinger, "Integration analysis of product decompositions," presented at the Proceedings of the ASME Design Engineering Technical Conferences - 6th International Conference on Design Theory and Methodology Minneapolis, MN, USA, 1994.
- [69] M. E. Sosa, S. D. Eppinger, and C. M. Rowles, "Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions," *Journal of Mechanical Design*, vol. 125(2), pp. 240-252, 2003.
- [70] C.-C. Huang and A. Kusiak, "Modularity in design of products and systems," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 28(1), pp. 66-77, 1998.
- [71] O. Asikoglu and T. W. Simpson, "A new method for evaluating design dependencies in product architectures," presented at the 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference Indianapolis, Indiana, USA, 2012.
- [72] S. Jung, T. W. Simpson, and O. Asikoglu, "Using interfaces to drive module definition: investigating the impact of a new design dependency measure," presented at the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (DETC2014-34555), Buffalo, New York, USA, 2014.
- [73] J. B. Dahmus, J. P. Gonzalez-Zugasti, and K. N. Otto, "Modular product architecture," *Design Studies*, vol. 22(5), pp. 409-424, 2001.
- [74] D. Krause, G. Beckmann, S. Eilmus, N. Gebhardt, H. Jonas, and R. Rettberg, "Integrated Development of Modular Product Families: A Methods Toolkit," in *Advances in Product Family and Product Platform Design*, T. W. Simpson, J. Jiao, Z. Siddique, and K. Hölttä-Otto, Eds., ed: Springer New York, 2014, pp. 245-269.
- [75] K. M. M. Hölttä and K. N. Otto, "Incorporating design effort complexity measures in product architectural design and assessment," *Design Studies*, vol. 26(5), pp. 463-485, 2005.
- [76] G. Erixon, "Modular Function Deployment - A method for product modularisation," Ph.D. thesis PhD thesis, The Royal Institute of Technology, Sweden, 1998.
- [77] X. Meng, Z. Jiang, and G. Q. Huang, "On the module identification for product family development," *The International Journal of Advanced Manufacturing Technology*, vol. 35(1-2), pp. 26-40, 2007.

- [78] A. Dobberfuhl and M. W. Lange, "Interfaces per module: Is there an ideal number?," presented at the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, San Diego, California, USA, 2009.
- [79] S. Jung and T. W. Simpson, "A Clustering Method Using New Modularity Indices and Genetic Algorithm with Extended Chromosomes," presented at the DSM 14 Proceedings of the 16th International DSM conference: Risk and Change management in complex systems, Paris, France, 2014.
- [80] S. Behdad, M. Kwak, H. Kim, and D. Thurston, "Simultaneous selective disassembly and end-of-life decision making for multiple products that share disassembly operations," *Journal of Mechanical Design*, vol. 132(4), pp. 041002-041002, 2010.
- [81] H.-E. Tseng, C.-C. Chang, and J.-D. Li, "Modular design to support green life-cycle engineering," *Expert Systems with Applications*, vol. 34(4), pp. 2524-2537, 2008.
- [82] M.-D. Shieh, W. Yan, and C.-H. Chen, "Soliciting customer requirements for product redesign based on picture sorts and ART2 neural network," *Expert Systems with Applications*, vol. 34(1), pp. 194-204, 2008.
- [83] H. J. Thevenot and T. W. Simpson, "Commonality indices for product family design: a detailed comparison," *Journal of Engineering Design*, vol. 17(2), pp. 99-119, 2006.
- [84] J. Ma and G. E. O. Kremer, "A Modular Product Design Approach with Key Components Consideration to Improve Sustainability," in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2014-35091*, 2014.
- [85] C. Eckert, P. J. Clarkson, and W. Zanker, "Change and customisation in complex engineering domains," *Research in Engineering Design*, vol. 15(1), pp. 1-21, 2004.
- [86] M. Giffin, O. de Weck, G. Bounova, R. Keller, C. Eckert, and P. J. Clarkson, "Change propagation analysis in complex technical systems," *Journal of Mechanical Design*, vol. 131(8), pp. 081001-081001, 2009.
- [87] D. V. Steward, "The design structure system: A method for managing the design of complex systems," *Engineering Management, IEEE Transactions on*, vol. EM-28(3), pp. 71-74, 1981.

- [88] P. J. Clarkson, C. Simons, and C. Eckert, "Predicting change propagation in complex design," *Journal of Mechanical Design*, vol. 126(5), pp. 788-797, 2004.
- [89] E. S. Suh, O. L. Weck, and D. Chang, "Flexible product platforms: framework and case study," *Research in Engineering Design*, vol. 18(2), pp. 67-89, 2007.
- [90] S. K. Moon, K. J. Park, and T. W. Simpson, "Platform design variable identification for a product family using multi-objective particle swarm optimization," *Research in Engineering Design*, vol. 25(2), pp. 95-108, 2014.
- [91] S. Chowdhury, A. Messac, and R. A. Khire, "Comprehensive product platform planning (CP3) framework," *Journal of Mechanical Design*, vol. 133(10), p. 101004, 2011.
- [92] S. Chowdhury, V. Maldonado, W. Tong, and A. Messac, "Comprehensive product platform planning (CP3) for a modular family of unmanned aerial vehicles," *ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE* 2013.
- [93] O. L. de Weck, E. S. Suh, and D. Chang, "Product family and platform portfolio optimization," in *ASME International Design Engineering Technical Conference, Chicago, Illinois*, 2003.
- [94] J. P. Gonzalez-Zugasti and K. N. Otto, "Modular platform-based product family design," in *ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Baltimore, Maryland, USA, 2000.
- [95] K. Fujita and H. Yoshida, "Product Variety Optimization Simultaneously Designing Module Combination and Module Attributes," *Concurrent Engineering*, vol. 12(2), pp. 105-118, 2004.
- [96] M. V. Martin and K. Ishii, "Design for variety: developing standardized and modularized product platform architectures," *Research in Engineering Design*, vol. 13(4), pp. 213-235, 2002.
- [97] S. K. Moon, T. W. Simpson, and S. R. T. Kumara, "A methodology for knowledge discovery to support product family design," *Annals of Operations Research*, vol. 174(1), pp. 201-218, 2010.
- [98] T. W. Simpson, A. Bobuk, L. A. Slingerland, S. Brennan, D. Logan, and K. Reichard, "From user requirements to commonality specifications: an

integrated approach to product family design," *Research in Engineering Design*, vol. 23(2), pp. 141-153, 2012.

- [99] A. Khajavirad, J. J. Michalek, and T. W. Simpson, "Solving the Joint Product Platform Selection and Product Family Design Problem: An Efficient Decomposed Multiobjective Genetic Algorithm with Generalized Commonality," in *Advances in Product Family and Product Platform Design: Methods & Applications*, W. T. Simpson, J. Jiao, Z. Siddique, and K. Hölttä-Otto, Eds., ed New York, NY: Springer New York, 2014, pp. 271-294.
- [100] R. Rai and V. Allada, "Modular product family design: Agent-based Pareto-optimization and quality loss function-based post-optimal analysis," *International Journal of Production Research*, vol. 41(17), pp. 4075-4098, 2003.
- [101] Z. Pirmoradi and G. G. Wang, "Recent Advancements in Product Family Design and Platform-Based Product Development: A Literature Review," presented at the ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No.:DETC2011-47959, Washington, DC, USA, 2011.
- [102] H. J. Thevenot, F. Alizon, T. W. Simpson, and S. B. Shooter, "An index-based method to manage the tradeoff between diversity and commonality during product family design," *Concurrent Engineering-Research and Applications*, vol. 15(2), pp. 127-139, 2007.
- [103] D. Robertson and K. T. Ulrich, "Planning for product platforms," *Sloan Management Review*, vol. 39(4), pp. 19-+, 1998.
- [104] S. K. Moon, J. Park, T. W. Simpson, and S. R. T. Kumara, "A Dynamic Multiagent System Based on a Negotiation Mechanism for Product Family Design," *Automation Science and Engineering, IEEE Transactions on*, vol. 5(2), pp. 234-244, 2008.
- [105] Y. Ji, R. J. Jiao, L. Chen, and C. Wu, "Green modular design for material efficiency: a leader-follower joint optimization model," *Journal of Cleaner Production*, vol. 41pp. 187-201, 2013.
- [106] Q. Yang, S. Yu, and A. Sekhari, "A modular eco-design method for life cycle engineering based on redesign risk control," *The International Journal of Advanced Manufacturing Technology*, vol. 56(9), pp. 1215-1233, 2011.
- [107] S. Yu, Q. Yang, J. Tao, and X. Xu, "Incorporating Quality Function Deployment with modularity for the end-of-life of a product family," *Journal of Cleaner Production*, vol. 87pp. 423-430, 2015.

- [108] Z. Wu, C. K. Kwong, C. K. M. Lee, and J. Tang, "Joint decision of product configuration and remanufacturing for product family design," *International Journal of Production Research*, pp. 1-14, 2015.
- [109] Q. Wang, D. Tang, L. Yin, M. A. Salido, A. Giret, and Y. Xu, "Bi-objective optimization for low-carbon product family design," *Robotics and Computer-Integrated Manufacturing*, vol. 41pp. 53-65, 2016.
- [110] W. Yan, C.-H. Chen, and W. Chang, "An investigation into sustainable product conceptualization using a design knowledge hierarchy and Hopfield network," *Computers & Industrial Engineering*, vol. 56(4), pp. 1617-1626, 2009.
- [111] Z. Siddique and D. W. Rosen, "On combinatorial design spaces for the configuration design of product families," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 15(2), pp. 91-108, 2001.
- [112] J. Jiao and Y. Zhang, "Product portfolio planning with customer-engineering interaction," *IIE Transactions*, vol. 37(9), pp. 801-814, 2005.
- [113] N. Lei and S. K. Moon, "A Decision Support System for market-driven product positioning and design," *Decision Support Systems*, vol. 69pp. 82-91, 2015.
- [114] S. L. Soh, S. K. Ong, and A. Y. C. Nee, "Application of Design for Disassembly from Remanufacturing Perspective," *Procedia CIRP*, vol. 26pp. 577-582, 2015.
- [115] M. Kwak and H. M. Kim, "Evaluating End-of-Life Recovery Profit by a Simultaneous Consideration of Product Design and Recovery Network Design," *Journal of Mechanical Design*, vol. 132(7), pp. 071001-071001, 2010.
- [116] G. Boothroyd, P. Dewhurst, and W. A. Knight, *Product design for manufacture and assembly*: CRC Press, 2010.
- [117] H. K. Rampersad, *Integrated and Simultaneous Design for Robotic Assembly: Product Development, Planning*: John Wiley & Sons, Inc., 1994.
- [118] S. N. Samy and H. ElMaraghy, "A model for measuring products assembly complexity," *International Journal of Computer Integrated Manufacturing*, vol. 23(11), pp. 1015-1027, 2010.

- [119] S. K. Das and S. Naik, "Process planning for product disassembly," *International Journal of Production Research*, vol. 40(6), pp. 1335-1355, 2002.
- [120] S. K. Das, P. Yedlarajiah, and R. Narendra, "An approach for estimating the end-of-life product disassembly effort and cost," *International Journal of Production Research*, vol. 38(3), pp. 657-673, 2000.
- [121] R. E. Thebeau, "Knowledge management of system interfaces and interactions from product development processes," M.S. Thesis, System design and management, Massachusetts Institute of Technology, USA, 2001.
- [122] G. Du, R. J. Jiao, and M. Chen, "Joint optimization of product family configuration and scaling design by Stackelberg game," *European Journal of Operational Research*, vol. 232(2), pp. 330-341, 2014.
- [123] A. S. Yigit, A. G. Ulsoy, and A. Allahverdi, "Optimizing modular product design for reconfigurable manufacturing," *Journal of Intelligent Manufacturing*, vol. 13(4), pp. 309-316.
- [124] S. K. Moon and D. A. McAdams, "A Market-Based Design Strategy for a Universal Product Family," *Journal of Mechanical Design*, vol. 134(11), p. 111007, 2012.
- [125] G. Erixon, "Modular Function Development MFD, Support for Good Product Structure Creation," presented at the DS 53: Proceedings of the 2nd WDK Workshop on Product Structuring Delft University of Technology, Netherlands, 1996.
- [126] J. Hirtz, R. B. Stone, D. A. McAdams, S. Szykman, and K. L. Wood, "A functional basis for engineering design: Reconciling and evolving previous efforts," *Research in Engineering Design*, vol. 13(2), pp. 65-82, 2002.
- [127] L. Y. Ljungberg, "Materials selection and design for development of sustainable products," *Materials & Design*, vol. 28(2), pp. 466-479, 2007.
- [128] M. I. Mazhar, S. Kara, and H. Kaebernick, "Remaining life estimation of used components in consumer products: Life cycle data analysis by Weibull and artificial neural networks," *Journal of Operations Management*, vol. 25(6), pp. 1184-1193, 2007.
- [129] S. Kara, M. Mazhar, H. Kaebernick, and A. Ahmed, "Determining the Reuse Potential of Components Based on Life Cycle Data," *CIRP Annals - Manufacturing Technology*, vol. 54(1), pp. 1-4, 2005.

- [130] P. Flach, *Machine Learning: The Art and Science of Algorithms that Make Sense of Data*. New York: Cambridge University Press, 2012.
- [131] K. Hölttä-Otto, V. Tang, and K. Otto, "Analyzing module commonality for platform design using dendrograms," *Research in Engineering Design*, vol. 19(2), p. 127, 2008.
- [132] S. M. Van Dongen, "Graph clustering by flow simulation," Ph.D. Thesis, Center for Mathematics and Computer Science, Utrecht University, Netherlands, 2000.
- [133] X. Lei, F. Wang, F.-X. Wu, A. Zhang, and W. Pedrycz, "Protein complex identification through Markov clustering with firefly algorithm on dynamic protein–protein interaction networks," *Information Sciences*, vol. 329(0), pp. 303-316, 2016.
- [134] S. Brohée and J. van Helden, "Evaluation of clustering algorithms for protein-protein interaction networks," *BMC Bioinformatics*, vol. 7(1), p. 488, 2006.
- [135] Y.-K. Shih and S. Parthasarathy, "Identifying functional modules in interaction networks through overlapping Markov clustering," *Bioinformatics*, vol. 28(18), pp. i473-i479, 2012.
- [136] J. S. Bernardes, F. R. Vieira, L. M. Costa, and G. Zaverucha, "Evaluation and improvements of clustering algorithms for detecting remote homologous protein families," *BMC Bioinformatics*, vol. 16(1), pp. 1-14, 2015.
- [137] S. Mudgal, B. Tinetti, L. Lyons, P. Lavelle, A. Cornier, and C. Sannier, "Preparatory studies for ecodesign requirements of EuPs (III): Lot 25: Non-tertiary coffee machines, Task 2: Economic and market analysis, Report for European Commission (DG ENER)," BIO Intelligence Service, Paris, France July 2011.
- [138] H. Baayen, "Eco-indicator 99 manual for designers.," ed: Ministry of Housing, Spatial Planning and the Environment, Hague, Netherlands, Available at this URL (https://www.pre-sustainability.com/download/EI99_Manual.pdf), 2000.
- [139] F.-M. Belz and K. J. Peattie, *Sustainability marketing: A global perspective*. Chichester: Wiley, 2009.
- [140] J. W. K. Chan and T. K. L. Tong, "Multi-criteria material selections and end-of-life product strategy: Grey relational analysis approach," *Materials & Design*, vol. 28(5), pp. 1539-1546, 2007.

- [141] J. A. Fava, K. Brady, S. B. Young, and K. Saur, "Sustainable strategies using life cycle approaches," *Environmental Progress*, vol. 19(2), pp. 61-64, 2000.
- [142] International Organization for Standardization, "Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication " in *ISO/TS 14067:2013*, ed, 2013.
- [143] C. B. Joung, J. Carrell, P. Sarkar, and S. C. Feng, "Categorization of indicators for sustainable manufacturing," *Ecological Indicators*, vol. 24pp. 148-157, 2013.
- [144] B. Moldan, S. Janoušková, and T. Hák, "How to understand and measure environmental sustainability: Indicators and targets," *Ecological Indicators*, vol. 17(0), pp. 4-13, 2012.
- [145] K. Lindow, R. Woll, and R. Stark, "A conceptual framework for sustainable engineering design," in *Leveraging Technology for a Sustainable World*, ed Berlin Heidelberg: Springer, 2012, pp. 197-202.
- [146] B. Steen, "A systematic approach to environmental priority strategies in product development (EPS): version 2000-general system characteristics," Centre for Environmental Assessment of Products and Material Systems at Chalmers University of Technology 1999.
- [147] Ecoinvent. *Ecoinvent database*, <<http://www.ecoinvent.org/>>.
- [148] M. Goedkoop and R. Spriensma, "The eco-indicator99: A damage oriented method for life cycle impact assessment: Methodology report," PRé Consultants B.V. 22 June 2001.
- [149] International Organization for Standardization, "Environmental management-Environmental performance evaluation-Guidelines " in *ISO 14031:2013(E)*, ed, 2013.
- [150] National Institute of Standards and Technology. *Sustainable manufacturing indicators repository* <<http://www.mel.nist.gov/msid/SMIR/index.html>>, Last access date: 30 July 2016. Available: <http://www.mel.nist.gov/msid/SMIR/index.html>
- [151] G. Liu, A. M. Baniyounes, M. G. Rasul, M. T. O. Amanullah, and M. M. K. Khan, "General sustainability indicator of renewable energy system based on grey relational analysis," *International Journal of Energy Research*, vol. 37(14), pp. 1928–1936, 2013.
- [152] V. H. Dale, R. A. Efroymson, K. L. Kline, M. H. Langholtz, P. N. Leiby, G. A. Oladosu, *et al.*, "Indicators for assessing socioeconomic

sustainability of bioenergy systems: A short list of practical measures," *Ecological Indicators*, vol. 26pp. 87-102, 2013.

- [153] B. S. Linke, G. J. Corman, D. A. Dornfeld, and S. Tönissen, "Sustainability indicators for discrete manufacturing processes applied to grinding technology," *Journal of Manufacturing Systems*, vol. 32(4), pp. 556-563, 2013.
- [154] J. Dai and J. Blackhurst, "A four-phase AHP-QFD approach for supplier assessment: a sustainability perspective," *International Journal of Production Research*, vol. 50(19), pp. 5474-5490, 2011.
- [155] C. Chen, J. Zhu, J.-Y. Yu, and H. Noori, "A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis," *European Journal of Operational Research*, vol. 221(2), pp. 348-359, 2012.
- [156] R. V. Rao, *Decision Making in Manufacturing Environment Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods* vol. 2. London: Springer-Verlag, 2013.
- [157] Y. Kuo, T. Yang, and G.-W. Huang, "The use of grey relational analysis in solving multiple attribute decision-making problems," *Computers & Industrial Engineering*, vol. 55(1), pp. 80-93, 2008.
- [158] H. V. Rowley, G. M. Peters, S. Lundie, and S. J. Moore, "Aggregating sustainability indicators: Beyond the weighted sum," *Journal of Environmental Management*, vol. 111(0), pp. 24-33, 2012.
- [159] J. A. Farris, R. L. Groesbeck, E. M. V. Aken, and G. Letens, "Evaluating the Relative Performance of Engineering Design Projects: A Case Study Using Data Envelopment Analysis," *IEEE Transactions on Engineering Management*, vol. 53(3), pp. 471-482, 2006.
- [160] S.-T. Lin, S.-J. Horng, B.-H. Lee, P. Fan, Y. Pan, J.-L. Lai, *et al.*, "Application of grey-relational analysis to find the most suitable watermarking scheme," *International Journal of Innovative Computing, Information and Control*, vol. 7(9), pp. 5389-5401, 2011.
- [161] S. K. Moon, H. S. Oh, J. A. Venture, J. K. Kim, and Y.-J. Yoon, "Service reliability improvement in manufacturing and operating systems," *International Journal of Precision Engineering and Manufacturing*, vol. 14(8), pp. 1401-1406, 2013.
- [162] U. Lindemann, M. Maurer, and T. Braun, *Structural complexity management*: Springer, 2009.

- [163] T. R. Browning, "Applying the design structure matrix to system decomposition and integration problems: a review and new directions," *Engineering Management, IEEE Transactions on*, vol. 48(3), pp. 292-306, 2001.
- [164] K. Otto, K. Hölttä-Otto, T. W. Simpson, D. Krause, S. Ripperda, and S. K. Moon, "Global Views on Modular Design Research: Linking Alternative Methods to Support Modular Product Family Concept Development," *Journal of Mechanical Design*, vol. 138(7), pp. 071101-071101, 2016.
- [165] T. R. Browning, "Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities," *IEEE Transactions on Engineering Management*, vol. 63(1), pp. 27-52, 2016.
- [166] E. C. Y. Koh, N. H. M. Caldwell, and P. J. Clarkson, "A method to assess the effects of engineering change propagation," *Research in Engineering Design*, vol. 23(4), pp. 329-351, 2012.
- [167] J. Hu and M.-A. Cardin, "Generating flexibility in the design of engineering systems to enable better sustainability and lifecycle performance," *Research in Engineering Design*, vol. 26(2), pp. 121-143, 2015.
- [168] J. F. Carriger and M. C. Newman, "Influence diagrams as decision-making tools for pesticide risk management," *Integrated Environmental Assessment and Management*, vol. 8(2), pp. 339-350, 2012.
- [169] N. Yodo and P. Wang, "Resilience Modeling and Quantification for Engineered Systems Using Bayesian Networks," *Journal of Mechanical Design*, vol. 138(3), p. 031404, 2016.
- [170] L. Uusitalo, "Advantages and challenges of Bayesian networks in environmental modelling," *Ecological Modelling*, vol. 203(3-4), pp. 312-318, 2007.
- [171] A. Detwarasiti and R. D. Shachter, "Influence diagrams for team decision analysis," *Decision Analysis*, vol. 2(4), pp. 207-228, 2005.
- [172] U. B. Kjærulff and A. L. Madsen, *Bayesian networks and influence diagrams: A guide to construction and analysis*. New York: Springer, 2013.
- [173] A. Zagorecki and M. Druzdzel, "An empirical study of probability elicitation under noisy-OR assumption," in *Proceedings of the 17th International Florida Artificial Intelligence Research Society*

Conference (FLAIRS2004), Miami Beach, Florida, USA, 2004, pp. 880-885.

- [174] J. Pearl, *Probabilistic reasoning in intelligent systems: networks of plausible inference*: Morgan Kaufmann Publishers Inc., 1988.
- [175] M. G. Morgan and M. Henrion, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge: Cambridge University Press, 1990.
- [176] X. Wu, V. Kumar, J. Ross Quinlan, J. Ghosh, Q. Yang, H. Motoda, *et al.*, "Top 10 algorithms in data mining," *Knowledge and Information Systems*, vol. 14(1), pp. 1-37, 2008.
- [177] E. Trillas and L. Eciolaza, *Fuzzy Logic: An Introductory Course for Engineering Students*. Switzerland: Springer International Publishing, 2015.
- [178] J. A. Harding, K. Popplewell, R. Y. K. Fung, and A. R. Omar, "An intelligent information framework relating customer requirements and product characteristics," *Computers in Industry*, vol. 44(1), pp. 51-65, 2001.
- [179] T. Takagi and M. Sugeno, "Fuzzy identification of systems and its applications to modeling and control," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. SMC-15(1), pp. 116-132, 1985.
- [180] J. S. R. Jang, "ANFIS: adaptive-network-based fuzzy inference system," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. 23(3), pp. 665-685, 1993.
- [181] R. Battisti and A. Corrado, "Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology," *Energy*, vol. 30(7), pp. 952-967, 2005.
- [182] PRé Consultants. (February, 2014). *Simapro software for LCA*. <<http://www.pre-sustainability.com/simapro>>. Available: <http://www.pre-sustainability.com/simapro>
- [183] P. Ghadimi, A. H. Azadnia, N. Mohd Yusof, and M. Z. Mat Saman, "A weighted fuzzy approach for product sustainability assessment: a case study in automotive industry," *Journal of Cleaner Production*, vol. 33pp. 10-21, 2012.
- [184] R. F. Dyer and E. H. Forman, "Group decision support with the Analytic Hierarchy Process," *Decision Support Systems*, vol. 8(2), pp. 99-124, 1992.

- [185] S. I. Gass, "Model World: The Great Debate—MAUT Versus AHP," *Interfaces*, vol. 35(4), pp. 308-312, 2005.
- [186] Norsys Software Corp. *Netica Application Software*, <https://www.norsys.com/index.html>.
- [187] P. Zwolinski and D. Brissaud, "Remanufacturing strategies to support product design and redesign," *Journal of Engineering Design*, vol. 19(4), pp. 321-335, 2008.
- [188] W. L. Ijomah, "Addressing decision making for remanufacturing operations and design-for-remanufacture," *International Journal of Sustainable Engineering*, vol. 2(2), pp. 91-102, 2009.
- [189] A. Atasu, V. D. R. Guide, and L. N. Van Wassenhove, "So what if remanufacturing cannibalizes my new product sales?," *California Management Review*, vol. 52(2), pp. 56-76, 2010.
- [190] X. Du, J. Jiao, and M. M. Tseng, "Architecture of Product Family: Fundamentals and Methodology," *Concurrent Engineering*, vol. 9(4), pp. 309-325, 2001.
- [191] J. Jiao, "Product platform flexibility planning by hybrid real options analysis," *IIE Transactions*, vol. 44(6), pp. 431-445, 2012.
- [192] J. Jiao, Y. Zhang, and Y. Wang, "A generic genetic algorithm for product family design," *Journal of Intelligent Manufacturing*, vol. 18(2), pp. 233-247, 2007.
- [193] L. Jiang and V. Allada, "Robust modular product family design using a modified Taguchi method," *Journal of Engineering Design*, vol. 16(5), pp. 443-458, 2005.
- [194] J. J. Michalek, P. Y. Papalambros, and S. J. Skerlos, "A Study of Fuel Efficiency and Emission Policy Impact on Optimal Vehicle Design Decisions," *Journal of Mechanical Design*, vol. 126(6), pp. 1062-1070, 2004.
- [195] J. J. Michalek, O. Ceryan, P. Y. Papalambros, and Y. Koren, "Balancing Marketing and Manufacturing Objectives in Product Line Design," *Journal of Mechanical Design*, vol. 128(6), pp. 1196-1204, 2005.
- [196] K. E. Train, *Discrete choice methods with simulation*. New York, NY, USA: Cambridge university press, 2009.

- [197] F. S. Koppelman and C. Bhat, *A Self Instructing Course in Mode Choice Modeling: Multinomial and Nested Logit Models*. USA: Prepared for U.S. Department of Transportation Federal Transit Administration, Available at this URL (http://www.caee.utexas.edu/prof/bhat/COURSES/LM_Draft_060131Final-060630.pdf), 2006.
- [198] X. G. Luo and C. K. Kuvong, "A multiobjective approach for optimal design of product line," in *International Conference on Advanced Technology of Design and Manufacture (ATDM 2010)*, Beijing, China, 2010, pp. 10-15.
- [199] C. B. Resende, C. G. Heckmann, and J. J. Michalek, "Robust Design for Profit Maximization Under Uncertainty of Consumer Choice Model Parameters Using the Delta Method," in *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2011-48409*, Washington, DC, USA, 2011, pp. 421-434.
- [200] Y. Zhang and J. K. Gershenson, "Questioning the Direct Relationship between Product Modularity and Retirement Cost," *The Journal of Sustainable Product Design*, vol. 2(1), pp. 53-68, 2002.
- [201] G. C. Canavos, "An Empirical Bayes Approach for the Poisson Life Distribution," *IEEE Transactions on Reliability*, vol. R-22(2), pp. 91-96, 1973.
- [202] J. Ma, M. Kwak, and H. M. Kim, "Demand Trend Mining for Predictive Life Cycle Design," *Journal of Cleaner Production*, vol. 68pp. 189-199, 2014.
- [203] T. W. Simpson and B. S. D'Souza, "Assessing Variable Levels of Platform Commonality Within a Product Family Using a Multiobjective Genetic Algorithm," *Concurrent Engineering*, vol. 12(2), pp. 119-129, 2004.
- [204] A. Konak, D. W. Coit, and A. E. Smith, "Multi-objective optimization using genetic algorithms: A tutorial," *Reliability Engineering & System Safety*, vol. 91(9), pp. 992-1007, 2006.
- [205] A. H. F. Dias and J. A. de Vasconcelos, "Multiobjective genetic algorithms applied to solve optimization problems," *IEEE Transactions on Magnetics*, vol. 38(2), pp. 1133-1136, 2002.
- [206] K. Deb, *Multi-objective optimization using evolutionary algorithms*. Chichester, New York: John Wiley & Sons, 2001.

- [207] K. Deb, *Multi-objective optimization using evolutionary algorithms*. Chichester, New York: John Wiley & Sons, 2008.

Appendix A: Bill of Material of Coffee Makers and Electric Shavers

In this appendix, products information that are not described in case studies of previous chapters are additionally represented here.

Table A-1. Bill of Materials of Coffee Makers for Case Study (a) HD7450, (b) HD7448, and (c) HD7458

(a)

	Part (HD7450)	Weight (g)	#Req'd	Material	Manufacturing Process
1	Bottom cover	80.5	1	PP	Injection moulding
2	Screw	4.3	4	Steel	Machining
3	Hot plate holder pin	15.8	1	Steel	Forming/Stamping
4	Screws	1.8	2	Steel	Machining
5	Silicon ring	1.8	1	Silicon	Extrusion
6	Hot plate	61.3	1	Steel	Forming
7	Casing for heater	55.2	1	PP	Injection moulding
8	Main cord	120.0	1	Copper	
9	Heater	118.2	1	Aluminium	Extrusion/Forming
10	Silicon tube	10.7	2	Silicon	Extrusion
11	Silicon tube	10.7	2	Silicon	Extrusion
12	Water tube set	14.7	1	PP	Injection moulding
13	One-way valve	0.6	1	PP	Injection moulding
14	Steam sprout	11.5	1	PP	Injection moulding
15	Water reservoir	243.2	1	PP	Injection moulding
16	Water tank cover	19.5	1	PP	Injection moulding
17	Filter basket	79.1	1	PP	Injection moulding
18	Spring	0.8	1	Steel	Forming
19	Filter	12.0	1	PP	Injection moulding
20	Lid of coffee maker	72.6	1	PP	Injection moulding
21	Glass cup	159.6	1	Glass	Glass moulding
22	Handle	45.8	1	PP	Injection moulding
23	Screw	0.9	1	Steel	Machining
24	Thin metal band	9.1	1	Steel	Machining
25	Screws	3.0	3	Steel	Machining
26	Casing	155.0	1	PP	Injection moulding
	Total weight	1307.7			

(b)

	Part (HD7448)	Weight (g)	# Req'd	Material	Manufacturing Process
1	Bottom cover	69.90	1	PP	Injection moulding
2	Screw	2.40	2	Steel	Machining
3	Hot plate holder pin	4.50	1	Steel	Forming/Stamping
4	Hot plate	58.80	1	Steel	Forming
5	Casing for heater	49.40	1	PP	Injection moulding
6	Heater clip	2.90	1	Steel	Forming
7	Main cord	120.00	1	Copper	
8	Heater	108.00	1	Aluminium	Extrusion/Forming
9	Silicon tube	12.10	2	Silicon	Extrusion
10	Silicon tube	12.20	2	Silicon	Extrusion
11	Water tube set	18.00	1	PP	Injection moulding
12	One-way valve	0.50	1	PP, rubber	Injection moulding
13	Water reservoir	173.50	1	PP	Injection moulding
14	Steam sprout	13.70	1	PP	Injection moulding
15	Filter	28.50	1	PP	Injection moulding
16	Filter basket	125.50	1	PP	Injection moulding
17	Spring	0.90	1	Steel	Forming
18	Lid of coffee maker	54.00	1	PP	Injection moulding
19	Glass cup	250.50	1	Glass	Glass moulding
20	Handle	64.50	1	PP	Injection moulding
21	Screw	1.30	1	Steel	Machining
22	Thin metal band	16.90	1	Steel	Machining
23	Bottom Casing	197.7	1	PP	Injection moulding
Total weight		1385.70			

(c)

	Part (HD7458)	Weight (g)	# Req'd	Material	Manufacturing Process
1	Bottom cover	107.90	1	PP	Injection moulding
2	Screw	3.70	3	Steel	machining
3	Hot plate holder pin	4.40	1	Steel	Forming/Stamping
4	Hot plate	58.50	1	Steel	Forming
5	Casing for heater	49.40	1	PP	Injection moulding
6	Main cord	110.30	1	Copper	
7	Heater clip	3.00	1	Steel	Forming
8	Clip cover	5.20	1	PP	Injection moulding
9	Heater	122.70	1	Aluminium	Extrusion/Forming
10	Silicon tube	12.00	2	Silicon	Extrusion
11	Silicon tube	12.00	2	Silicon	Extrusion
12	Water tube set	17.80	1	PP	Injection moulding
13	One-way valve	0.60	1	PP, rubber	Injection moulding
14	Water reservoir	275.20	1	PP	Injection moulding
15	Steam sprout	13.00	1	PP	Injection moulding
16	Steel cover for water reservoir	68.60	1	Steel	Forming
17	Filter basket	85.00	1	PP	Injection moulding
18	Spring	0.90	1	Steel	Forming
19	Lid of coffee maker	71.60	1	PP	Injection moulding
20	Glass cup	236.70	1	Glass	
21	Handle	57.30	1	PP	Injection moulding
22	Screw	1.00	1	Steel	machining
23	Thin metal band	10.80	1	Steel	machining
24	Casing	178.80	1	PP	Injection moulding
Total weight		1506.40			

Table A-2. Bill of Materials of Electric Shavers for Case Study (a) AT600 and (b) AT750**(a) AT600**

	Part name	Quantity of parts	Material type	Manufacturing process	Image
1	Upper blade cover	1	ABS Plastic	Injection moulding
2	Blade cover	2	Stainless steel	Die forming
3	Blade	2	Stainless steel	Die forming
4	Blade holder	1	Polyoxymethylene (POM)	Injection moulding
5	Main body cap	1	Polycarbonate (PC)	Injection moulding
6	On/Off spring	1	Stainless steel	Die forming
7	On/Off face button	1	Polycarbonate (PC)	Injection moulding
8	Gear module	1	Polypropylene + 50% Glass Fibre	Injection moulding
9	Secondary gear	1	Nylon	Injection moulding
10	Main motor gear	1	Nylon	Injection moulding
11	Gear module cover	1	PA 6 Polyamide + 40% Glass Fibre	Injection moulding

	Part name	Quantity of parts	Material type	Manufacturing process	Image
12	Top outer housing	1	ABS Plastic	Injection moulding
13	LED power cap	1	Expoxy	Injection moulding
14	Microswitch cover	1	Rubber	Moulding
15	Microswitch cover support	1	Stainless steel	Blanking
16	Inner body housing	1	Polyoxymethylene (POM)	Injection moulding
17	Motor	1	Multiple Components	Custom process
18	Printed circuit board	1	Copper Laminates	Custom process
19	Rechargeable battery	1	Multiple Components	Custom process
20	Charging pin connectors	2	Stainless steel	Die forming
21	Gasket	1	Rubber	Moulding
22	Bottom casing	1	ABS Plastic	Injection moulding

(b) AT750

	Part name	Quantity of parts	Material type	Manufacturing process	Image
1	Upper blade cover	1	PA 6 Polyamide + 60% Glass Fibre	Injection moulding
2	Blade cover	3	Stainless steel	Die forming
3	Blade	3	Stainless steel	Die forming
4	Blade holder	1	Polyoxymethylene (POM)	Injection moulding
5	Upper body cap	1	Polycarbonate (PC)	Injection moulding
6	Gear module	1	Polypropylene + Thermoplastic Elastomer	Injection moulding
7	Secondary gear	1	Nylon	Injection moulding
8	Main motor gear	1	Nylon	Injection moulding
9	Gear module cover	1	PA 6 Polyamide + 40% Glass Fibre	Injection moulding
10	Inner body housing	1	ABS Plastic	Injection moulding
11	Motor	1	Multiple Components	Custom process

	Part name	Quantity of parts	Material type	Manufacturing process	Image
12	Printed circuit board	1	Copper Laminates	Custom process
13	Rechargeable battery	1	Multiple Components	Custom process
14	Inner body housing cover	1	ABS Plastic	Injection moulding
15	External body front cover 3	1	Polypropylene	Injection moulding
16	External body front cover 2	1	ABS Plastic + Polyamide	Injection moulding
17	External body front cover 1	1	Polycarbonate + ABS Plastic + Thermoplastic	Injection moulding
18	External body back cover	1	ABS Plastic + Polyamide	Injection moulding