2015

MATHEMATICAL MODELING FOR PLATFORM-BASED PRODUCT CONFIGURATION CONSIDERING TOTAL LIFE-CYCLE SUSTAINABILITY

Tian Lan
University of Kentucky, lantian8827@gmail.com

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Tian Lan, Student

Dr. Fazleena Badurdeen, Major Professor

Dr. James McDonough, Director of Graduate Studies

MATHEMATICAL MODELING FOR PLATFORM-BASED PRODUCT CONFIGURATION CONSIDERING TOTAL LIFE-CYCLE SUSTAINABILITY

THESIS

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

By

Tian Lan

Lexington, Kentucky

Director: Dr. Fazleena Badurdeen, Associate Professor

Department of Mechanical Engineering

University of Kentucky, Lexington, KY

Abstract

MATHEMATICAL MODELING FOR PLATFORM-BASED PRODUCT CONFIGURATION CONSIDERING TOTAL LIFE-CYCLE SUSTAINABILITY

Many companies are using platform-based product designs to fulfill the requirements of customers while maintaining low cost. However, research that integrates sustainability into platform-based product design is still limited. Considering sustainability during platform-based design process is a challenge because the total life-cycle from pre-manufacturing, manufacturing and use to post-use stages as well as economic, environmental and societal performance in these stages must be considered. In this research, an approach for quantifying sustainability is introduced and a mathematical model is developed for identifying a more sustainable platform. Data from life-cycle assessment is used to quantify environmental factors; criteria from the Product Sustainability Index (ProdSI) are used to quantify societal factors. The Analytic Hierarchical Process method is used to assess relative importance of societal factors and the weighted sum method is used in the objective function for overall multi-objective optimization. A bicycle platform configuration is used as a case study to demonstrate the application of the model. The relationship between commonality of the platform and sustainability performance is analyzed.

Keywords: Sustainability, Product family design, Platform-based product configuration, Life Cycle Assessment, Optimization

Tian Lan

Student's Signature

05/31/2015

Date

MATHEMATICAL MODELING FOR PLATFORM-BASED PRODUCT CONFIGURATION CONSIDERING TOTAL LIFE-CYCLE SUSTAINABILITY

By

Tian Lan

Lexington, Kentucky

Dr. Fazleena Badurdeen

Director of Thesis

Dr. James McDonough

Director of Graduate Studies

05/31/2015

Date

Acknowledgements

I would like to express my sincere thanks to the many people who have assisted in the completion of my thesis for the University of Kentucky Department of Mechanical Engineering. Firstly, I would like to express deepest gratitude to my advisor, Dr. Fazleena Badurdeen, for her continuous guidance, financial support, and patience during my graduate studies. Dr. Badurdeen provided inspiration for my research topic selection. I certainly would not have been able to finish my thesis without her support and constructive feedback.

Secondly, I would like to thank Dr. Keith Rouch and Dr. Kozo Saito for serving as thesis committee members. Both of these faculty members reviewed my thesis and gave me valuable suggestions on how to clarify my research question and write the actual thesis. Furthermore, I must thank each of them for their time and valuable advice during the defense process.

Thirdly, I would like to thank all of the former and current group members of Dr. Badurdeen's team. I learned many things from our group meetings and received much assistance from team members. Additionally, I want to thank all the faculty members and staff in the Department of Mechanical Engineering and the Institute for Sustainable Manufacturing for their assistance throughout the duration of my master's program.

Lastly, I would like to express gratitude to my family and friends for their moral support. Thank you for helping me to survive all of the year's stress and not allowing me to give up. I would never have reached this point without your faithful encouragement and support.

Table of Contents

List of Tables

List of Figures

1. Introduction

The human population has increased from 2 billion to over 6 billion during the last century. This population growth has dramatically increased worldwide emissions and energy consumption due to intensive environmentally harmful human activities that include the burning of fossil fuels, deforestation, and land use changes. As a result, there are rising concerns about global warming, pollution, and waste around the world (Khasreen et al. 2009). "In 2006, the total output of the U.S. manufacturing sector (in the form of variety of products) had a gross value of 5.3 trillion dollars. These products were responsible for approximately 84% of energy-related carbon dioxide emissions and 90% of energy consumption in the industrial sector" (See Figure 1 & 2). Across the planet, human activity now adds as much as 7 billion tons of carbon dioxide to the atmosphere each year (Ramani, et al. 2010). Increasingly more serious environmental and social concerns and corresponding regulations are greatly impacting the manner in which companies design new products.

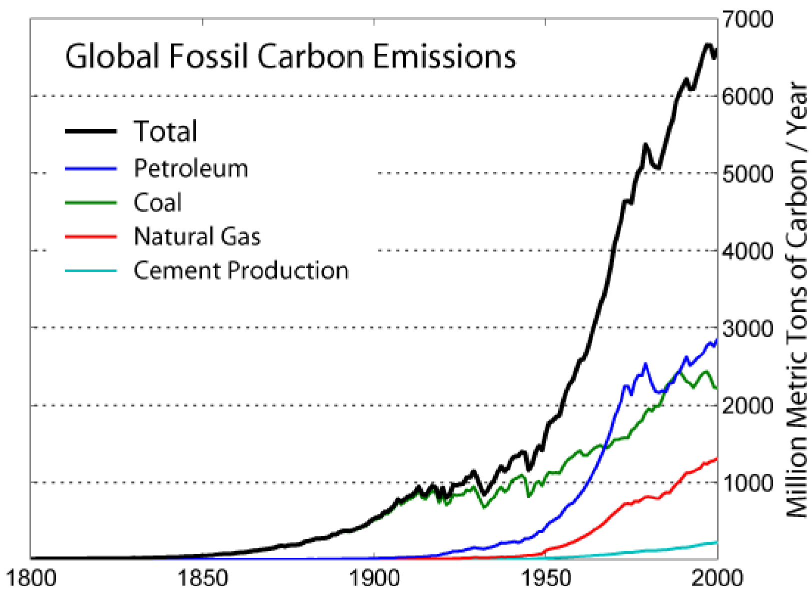

Figure 1: Global Fossil Carbon Emissions (Source: Wikimedia Commons)

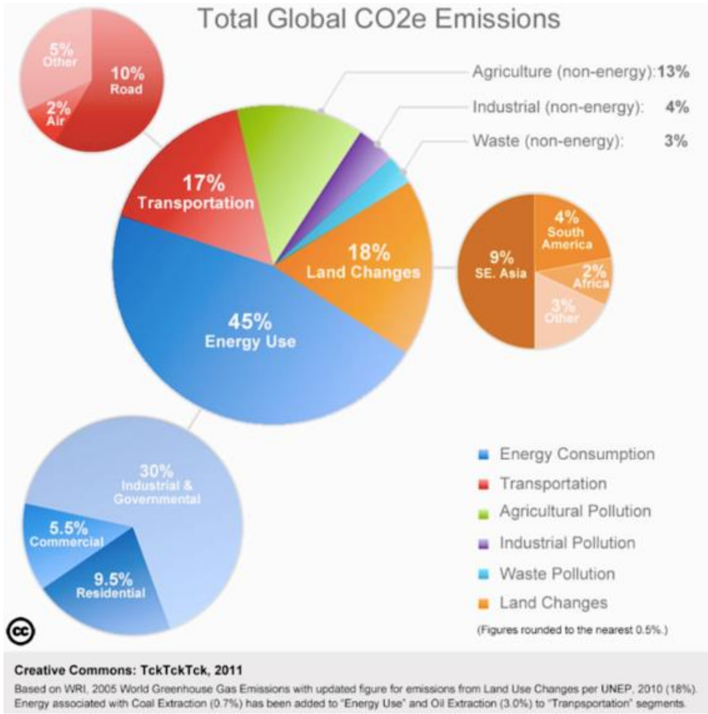

Figure 2: Total Global CO_2 Emissions (source: http://tcktcktck.org/2011/08/top-climate-solutions/317)

Sustainability and sustainable product design can help alleviate this urgent problem. Sustainable product design means that economic, environmental, and societal factors are all considered during the product design process in total life-cycle stages from pre-manufacturing to post use (See Figure 3). In order to account for sustainability in the product design, a variety of methods and tools have been developed. Design for Environment (DfE) is a method that integrates environmental considerations into product and process engineering design procedures (Ramani, et al. 2010). Life Cycle Assessment (LCA) has been widely adopted to evaluate environmental impact during the life-cycle of a product (Hendrickson, et al. 1998). The Eco-effective product design method integrates environmental aspects into the earliest design phases to improve environmental performance (Frei, 1998). Design for disassembly (DFD) is a method that considers the ease of disassembly for easier maintenance, recovery, and reuse of components (Lambert, et al. 2004). Tools based on different strategies have also been developed to fulfill this requirement. Examples include tools based on LCA (Devanathan, et al. 2010), checklists (Luttropp, et al. 2006), and quality function deployment (QFD) (Chan, et al. 2002). These methods and tools are effective in reducing the environmental impact of products to increase sustainability. However, these methods only focus on the design of individual products. Given the existing market conditions, companies need different products that can be designed at low cost to meet the needs of a variety of customers.

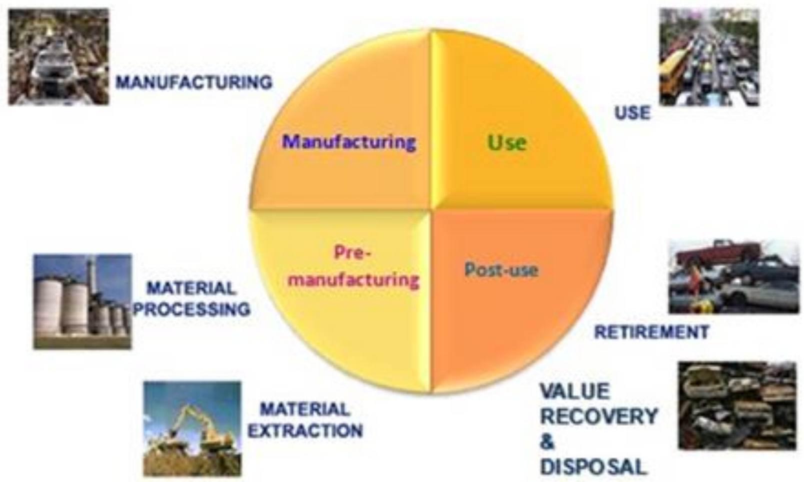

Figure 3: Life cycle of product (Badurdeen, 2009)

In order to fulfill the requirements of all customers and be successful as a business, many companies are using product families and platform-based product development to provide sufficient variety for the market while simultaneously maintaining low cost (Simpson, 2004). A product family is a group of related products derived from a product platform to satisfy a variety of market niches (Simpson, et al. 2006). A product platform can be defined as 'the collection of assets [i.e., components, processes, knowledge, people, and relationships] that are shared by a set of products' (Robertson, et al. 1998). With this definition, sharing product components can result in benefits to cost, speed (time to market), flexibility (product variety and product customization) and product quality. Component sharing is one of the key characteristics of product family and platform design and is utilized to increase product variety and reduce cost. An expanding interest in component sharing has resulted in the development of product family design and platform design (Kwak , et al. 2011).

There is considerable research in platform-based product family design. Most of the research focuses on the optimization of product family design. Two approaches are created for product family design, a top-down (proactive platform) approach and a bottom-up (reactive redesign) approach. Two types of product family, module-based product family and scale-based product family, are also created (Simpson, 2004). Much research has been conducted based on a different approach and different type of product family. For example, there are methods that use a single-stage approach with physical programming (Messac, et al. 2002), a genetic algorithm-based approach (D'Souza , et al. 2003), and a combined use of a multi-agent framework & quality loss function (Rai, et al. 2003). A fuzzy goal programming model is also proposed to examine multiple-platform architecture by maximizing overall utility and minimizing the total production cost (Tyagi, et al. 2012).

It must be noted that there is no research in product family design that considers total life-cycle sustainability during optimization. Most studies consider very few sustainability factors, which include product family design from a re-use perspective (Xu, et al. 2007), quantitative model for assessing product family design from an end-of-life perspective (Kwak, et al. 2011), and identifying sets of components that contain sensitive information in the product family designing process (Arciniegas, et al. 2012). All sustainability factors in the total life-cycle should be considered for a comprehensive assessment from the pre-manufacturing and manufacturing stages to the use and post-use stages. Otto et al. (2009) introduce an assessment tool to evaluate a product platform considering a number of sustainability factors using a set of metrics (Hölttä-Otto, et al. 2006). However, the assessment tool is not a quantitative model and cannot be used during the early design optimization process. In fact, no mathematical models exist that consider all total life-cycle factors in product platform design process. Therefore, developing tools with the consideration of sustainability is highly important in product family and platform design.

This research introduces a mathematical model tool to evaluate total life-cycle sustainability and identify the best platform for platform-based product design. In particular, economic, environmental, and societal factors in the four life-cycle stages are considered, which include pre-manufacturing, manufacturing, use, and post-use stages (See Figure 3). A quantitative model for assessing environmental and societal factors will be introduced, and data from Life Cycle Assessment (LCA) software, SimaPro, will be exported to the model to evaluate environmental factors, CO_2 emission, and energy consumption. While it is very difficult to mathematically express societal factors, this research introduces an empirical function and uses some components in Product Sustainability Index (ProdSI) to address the problem (Shuaib, et al. 2014). The units of criteria considered are optimized in the model. Therefore, data from an existing product will be used to normalize all the factors. Sustainability performance requires simultaneous consideration of economic, environmental, and societal factors. The weighted sum method will be used to solve this multiple objective optimization problem.

This thesis is organized according to the following outline: the literature review is presented in Section 2 and the proposed methodology is described in Section 3. A mathematical model to assess sustainability of platform based design is presented in Section 4. A case study is presented in Section 5 and study conclusions and discussion of future work are presented Sections 6 and 7, respectively.

2. Literature Review

This chapter introduces definitions and relevant research for sustainability, sustainable product design, LCA, and product family design. First, the current research will be discussed regarding sustainable product design and common concept methodology. Second, product family design research will be presented. Third, new research that connects sustainability and product family design will be introduced. The advantages of sustainable product family design will also be reported.

2.1 Sustainable Product Design

Over time, the global economic growth and industry will result in significant increases in global fuel demand, material requirements, and CO_2 emissions. As a result, sustainability will continue to be a critical issue for all of society to aim for more significant reductions to the overall environmental impact of industry across the globe (Mayyas, et al. 2012). Manufacturing is the primary contributor to the total CO_2 emissions. For example, the U.S. manufacturing sector has accounted for $\$1.65 \times 10^{12}$ (12.3%) of industry gross domestic product, but has been responsible for 36% of carbon dioxide emissions within the U.S. industrial sector, which has great impact on the environment (Haapala, et al. 2013). However, manufacturing plays a critical role within modern socio-economic systems and is a valuable contributor to wealth generation and offer jobs to thousands of peoples, particularly in developing economies. Industrial companies are increasingly forced to become more eco-efficient and to produce green products/systems in response to these emergency concerns (Haapala, et al. 2013). As a result, Sustainable Manufacturing is an emergent concept that is not only fashionable but a real need to be pursued (Cerri, et al. 2014). Many methods and tools have been developed to address these urgent requirements.

In order to achieve the target of sustainability, a wide range of concepts and methodology have been proposed to solve the problem. Some examples include the following: Design for X (DfX), Design for the Environment (Eco-design), Design for Disassembly, and Design for Recycling. The following section will provide a comprehensive review of these methodologies.

2.1.1 Design for X

Design for X includes Design for Manufacturing, Design for Assembly, and other "Design for's" or "-abilities" (e.g., Design for Quality, Design for Maintainability, Design for Disassembly, and Design for Recyclability).

Design for Manufacturing is defined as "the full range of policies, techniques, practices, and attitudes that cause a product to be designed for the optimum manufacturing cost, the optimum achievement of manufacturing quality, and the optimum achievement of life-cycle support, serviceability, reliability, and recyclability" (Stoll, 1990). In order to achieve the objectives of Design for Manufacturing, product concepts need to be identified for easy manufacturing, components need to be designed for ease of manufacturing and assembling, and manufacturing process design and product design need to match the market requirements (Stoll, 1988). Many tools have already been developed for Design for Manufacturing to assist in integrating product and process (e.g., three dimensional CAD/CAM modeling and Moldflow) (Kuo, et al. 2001). Group Technology (GT), Failure

Mode and Effect Analysis (FMEA), and value analysis are also tools that have been developed to achieve Design for Manufacturing targets (Chiu, et al. 2012).

2.1.2 Design for Environment

Due to the increasing number of environmental laws and public concern for environmental pollution and limited natural resources, customers are increasingly focused on material use for production, the production process, and energy consumption and waste accumulation of the production process (Madu, et al. 2002). As a result, environmental issues have been recognized as major challenges and environmentally conscious design, or green manufacturing are being proposed to meet these challenges. Design for environment (DFE) is a "practice by which environmental considerations are integrated into product and process engineering design procedures. DFE practices are meant to develop environmentally compatible products and processes while maintaining product, price, performance, and quality standards" (Ramani, et al. 2010). Checklists, Performance Indicators, Goals and decision checkpoints are usually used by company within the product development process. Quality management system (ISO 9001) and environmental management systems (ISO 14001) also are used to integrate all the tools to ensures the consistent application of DfE and continue improvement of environmental performance (Ilgin, et al. 2010).

Quality Function Deployment (QFD) is a "method wily to transform qualitative user demands into quantitative parameters, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process" (Akao, 1994) and was first developed by Dr. Yoji Akao. QFD is a design work tool for the early design stage of product development. A “QFD for environment (QFDE)” is develop by considering environmental aspects (environmental VOC (Voice of the Customer) and environmental EM) into QFD to examine environmental and traditional product requirements together (Masui, et al. 2003). A new QFD method is developed by considering environmental impact based on traditional QFD. Sakao (2007) proposed a new methodology to connect three tools together, LCA (Life Cycle Assessment), QFDE (quanlity function deployment for environment), and TRIZ (theory of inventive problem solving). The requirements of customers and environment are considered first. The voice of recyclers, production engineers, and users within the product life cycle are also integrated with 11 environmental requirements, VOE (Voice of Environment) (Sakao, 2007). VOE is weighted and considered a requirement of the customer and environment. QFDE and eco-VA (Value Analysis) is then adopted to incorporate three major aspects of product development, which include quality, cost, and speed within the context of the environment. TRIZ is then employed to help designers find improvement solutions (Sakao, 2007). However, there is one disadvantage of QFD based tool. The correlation between environmental factors and product characteristics is completely based on the experience of the designer.

2.1.3 Design for Disassembly

Remanufacturing is a new approach for increasing sustainability and reducing CO_2 emissions. The component is reused after remanufacturing. The manufacturing process of the component is eliminated and, as a result, energy consumption and waste accumulation is reduced. In order to remanufacture the components, disassembly processes are needed. In response, Design for Disassembly is proposed to remanufacture more components and simultaneously save more money and energy. The product that is designed for remanufacturing is easier to disassemble with more money and energy saved as compared to the product that is harder to disassemble. There are three major components of Design for Disassembly: (1) modeling and representation of product disassembly sequences; (2) disassembly process planning; and (3) disassembly system design and line balancing (Tang, et al. 2002).

The optimal disassembly sequence of the product is one of the most important decisions. All research for disassembly sequence can be divided into four groups: connection graph, direct graph, AND/OR graph, and disassembly Petri net (Tang, et al. 2002). Chu proposed a CAD-based approach that could change the combination of parts, select the assembly method, and rearrange the assembly sequence automatically with Genetic Algorithm (GA) techniques (Chu, et al. 2009). An analytic network process (ANP) method is created to evaluate all the alternative connections, including discrete fasteners, integral attachments, adhesive bonding, energy bonding, and other connectors (Güngör, 2006). A novel concept of eco-architecture is proposed to improve the ease of disassembly from the end-of-life view point. The product is represented as an assembly of EOL and a systematic approach is introduced to identify the optimal eco-architecture (Kwak, et al. 2009).

2.1.4 Design for Recycling

Design for Recycling is different from Design for Disassembly. Design for Recycling needs material reproduction and the component cannot be used directly in the product. Materials play the key role in Design for Recycling. Choosing materials that can be recycled means that materials can be reused again. Material recycling minimizes the consumption of raw material, reduces waste and air pollution during production, and reduces energy consumption (Mayyas, et al. 2012).

Many tools are also created for Design for Recyclability. A metric is proposed to determine the best separation process in the early design phase and two design guidelines to two types of separation are discussed. A simple method for determining the appropriate separation process in the early stages of design is presented (Coulter, et al. 1998). A mathematical model is proposed to evaluate products for bulk recycling by determining the cumulative net profit/cost as materials separation proceeds. The paper deals with the analysis of materials separation, which determines the least cost or maximum profit level of materials separation. As a result, it can be used for the evaluation of product designs for efficient bulk recycling and the combination of disassembly and bulk recycling (Knight, et al. 2000). Liu et al. (2002) developed a procedure for recyclability assessment through integrating AHP and Neural Network (NN). The main product recyclability influencing factors are refined with the AHP method and then the size of the neural network is reduced. Boon et al. (2002) develop a new method to explore the electronic goods recycling infrastructure by identifying the factors that most influence the profitability of end of life processing of PCs (Boon, et al. 2002). A computer-based tool called ENDLESS was proposed to calculate the Global Recycling Index with a Multi-Attribute Decision-Making method, which considers energy, environmental, technical and economic indicators. This tool can help the designer choose the product with the highest recyclability potential from a set of different alternatives with a weight assigned to each parameter with the experience of designers (Ardente, et al. 2003). A methodology called CHAMP (Chain Management of Materials and Products) was proposed to improve the recyclability of a fiber optic cable design. CHAMP combines elements of process and design engineering with life cycle approaches to enable the user to explore technical, economic, and environmental consequences of different materials, and process and technological options, including material recovery and recycling (Wright, et al. 2005). A DFR (Design for Recycling) methodology was proposed to identify economically optimum recycling strategies by combining dismantling, shredding, and post-shredding activities. In response, given recycling and reuse rates are achieved. This new approach includes post-shredding sorting of materials and subsequent recycling and is an end-of-life processing strategy (Ferrão, et al. 2006). An analytical framework is created to quantify the environmental and economic benefits of DFR for plastic computer enclosures during the design process with straightforward metrics that can be aligned with corporate environmental and financial performance goals (Masanet, et al. 2007). A prototype system is proposed for the translating of the recyclability norms in textual form into constraints which can be propagated throughout the product structure in order to identify the inconsistencies between the present design and a given norm (Houe, et al. 2007, Ilgin, et al. 2010).

2.1.5 Material Selection

Selection of materials for a particular application is primarily affected by the mechanical factors of weight and processability (Ilgin, et al. 2010). Increasingly more designers are considering environmental impact during the material selection process of product design. In order to address growing environmental concerns, many researchers are currently working on material selection for sustainable product design.

A selection procedure is created that elaborates data on the conventional and environmental properties of materials and processes, relates the data to the required performance of product components, and calculates the values assumed by functions that quantify the environmental impact over the whole life-cycle and the cost resulting from the choice of materials (Giudice, La et al. 2005). A Grey Relational Analysis (GRA)-based Multi Criteria Decision Making (MCDM) approach is created to integrate methodology of performing an order pair of materials and end-of-life product strategy for the purpose of material selection. Grey relational analysis is used to solve the multi-criteria problem and the multi-criteria weighted average is proposed in the decision-making process in order to rank the materials according to several criteria (Chan, et al. 2007). An integration of artificial neural networks (ANN) with genetic algorithms (GAs) is proposed to optimize the multi-objectives of material selection while considering technical, economic, and environmental factors. Evaluation indicators of materials are presented and environmental impacts are calculated by the Life Cycle Assessment method (Zhou, et al. 2009). A life cycle engineering (LCE) approach is proposed to support material selection, integrating the performance of the material for specific application in technological, environmental, and economical dimensions throughout the duration of the product. The "best material domains" is identified through comparing a set of candidate materials and the aggregation of technical, economic, and environmental dimensions. Finally, the "best material domains" are presented in a ternary diagram (Lin, 2006). A methodology for material selection in green design with concern for toxic impact is proposed with a price competition model. Material alternatives are determined in each of the multiple market life-cycle stages, while considering customer utility function and environmental taxation (Lin, 2006).

2.1.6 LCA

Life Cycle Analysis (LCA) is a method used to “evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal”(Ilgin, et al. 2010). LCA methodology is based on ISO 14040 and the usage of LCA that began in the 1960s. LCA was first used in a study conducted by the Coca-Cola company to quantify the environmental effects of packaging from cradle to grave (Khasreen, et al. 2009). Four main phases are included for the LCA analysis. First, goal definition and scope assessment, which defines the boundary of the system. Second, inventory analysis. Material and energy balance are performed here. Environmental burdens also are quantified here. Third, impact assessment. Aggregation of the burdens into generalized impact categories and impact characterization and aggregation of the environmental impacts into a single index happen in this phase. The final phase is improvement assessment. All the possibilities are identified for improving the performance of the system (Khan, et al. 2004).

An environmentally responsible assessment matrix is proposed to simplify the process of LCA (Graedel, et al. 1996). LCA is used to analyze disassembly trees after a graph-based heuristic method for disassembly analysis of end-of-life is adopted. The disassemblibility and recyclability of products is evaluated with LCA analysis results (Kuo, 2006). LCA is also used to assess the environmental performance of alternative solid waste management. Three selected scenarios are compared and the results quantify the relative advantages and disadvantages of different management schemes. As a result, some possible improvements can be suggested (Arena, et al. 2003). Current Environment Impact Assessment (EIA) methodologies are proposed with LCA and Artificial Neural Network

(ANN). ANN is used to estimate the missing data and LCA is used to obtain Life Cycle Assessment (LCA) information for major components in the study (Li, et al. 2008).

LCA is only applied at the end of the design process. LCA analysis is time and resource consuming because of the level of product detail information needed. Thus, complete LCA can only be used to evaluate the environmental impact of an existing product and it is difficult to apply at the design stage (Chiu, et al. 2012).

2.1.7 Product Service System

Product Service System (PSS) is another approach that can increase environmental benefits and other product issues such as profit and competitiveness. PSS can be defined as "a system of products, services, networks partners and supporting infrastructure that is economically feasible, competitive, and satisfies customer needs. It offers dematerialized solutions that minimize the environmental impact of consumption" (Baines, et al. 2007).

Most research divides the PSS into three categories, which include the following: product-oriented services, use-oriented services, and result-oriented services (Baines, et al. 2007). ISCL methodology is proposed to integrate service CAD and life cycle simulator, CAD/CAE tool for PSS design. Service CAD is used to support systematic generation of alternative service options through the relationship between activities and corresponding service contents and channels. LCS is used to evaluate the life cycle costs of different options by observing the dynamic state of products (Komoto, et al. 2008). An industrial PSS (IPS^2) is proposed to generate the principle solutions to meet specific customer requirements. The method can support an IPS^2 designer in generating heterogeneous IPS^2 concept models with a model-based approach in the early phase of development (Welp, et al. 2008). Wijekoon presented a new methodology to evaluate and optimize sustainability of customizable product-service systems while considering economic, environmental, and societal constraints and activities across the total product lifecycle (Wijekoon, 2011).

2.1.8 Methodology

In order to balance economic, environmental, and societal factors, a plethora of methodology has been proposed to design for sustainability. In the 1990's, the 3R methodology, reduce, reuse and recycle, was introduced to focused on environmentally benign manufacturing (Badurdeen, et al. 2009). However, this methodology is not a comprehensive approach, and does not include all four stage of total life cycle, pre-manufacturing, manufacturing, use, and post-use. In order to solve this problem, 6R methodology was developed to establish a framework for sustainability design (Jawahir, 2008). 6R methodology details are shown in Figure 5.

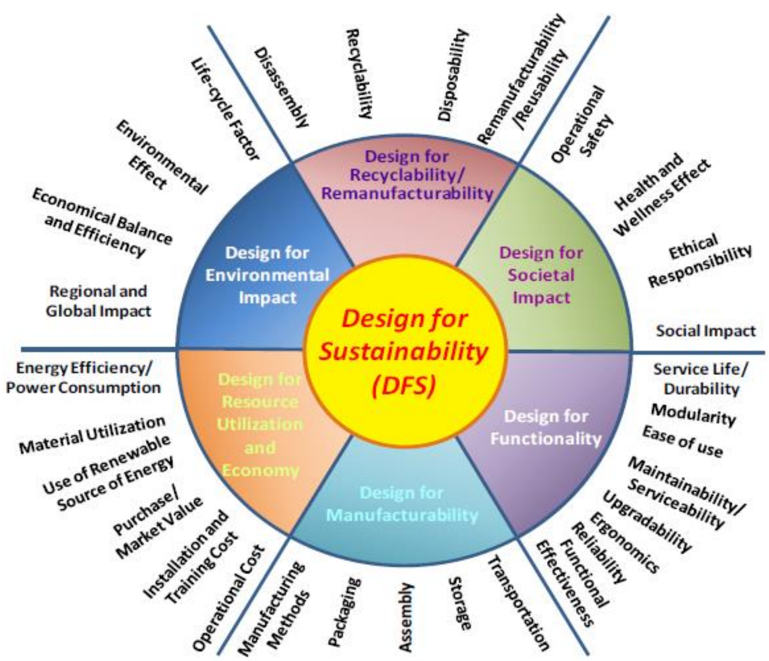

Figure 4: Elements of product design for sustainability (Jawahir, 2008)

The 6R methodology achieved the Triple Bottom Line (TBL) aspects of Economy, Environment and Society and considered all four life cycle stages. This integrated approach for developing sustainable products is shown in Figure 5 (Wijekoon, 2011).

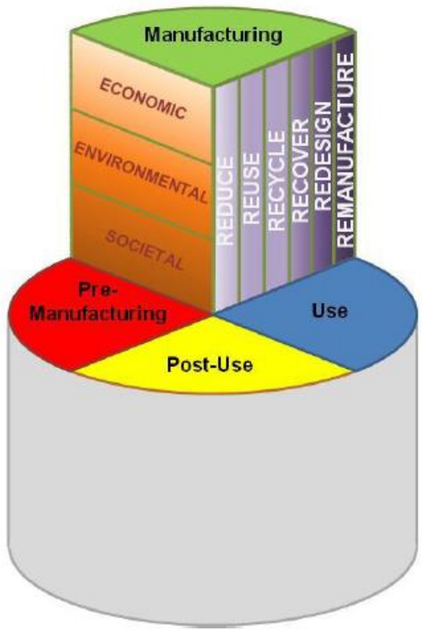

Figure 5 Application of the 6R's across Product Lifecycle Stages for TBL (Badurdeen, et al. 2009)

A sustainable product conceptualization system (SPCS) has been proposed by Yan et al. (2009). In this methodology, general sorting and design knowledge hierarchy (DKH) are used to generate product platform. Morphological configuration is used to generate initial design options. The initial design space is narrowed down with the Hopfield network based on design criteria of domain experts. The sustainability-cost pairs are generated based on rated sustainability cost criteria to select the preferred design options for sustainable product conceptualization (Yan, et al. 2009). A new methodology is proposed for integrating sustainability considerations into process design in the early design stage. The methodology leads to the most sustainable performance of the plant and product over their whole life cycles by enabling identification of relevant sustainability criteria and indicators, comparison of alternatives, and sustainability assessment of the overall design and identification of 'hot spots' in the life cycle of the system (Azapagic, et al. 2006). Detailed information for these process is shown in Figure 6.

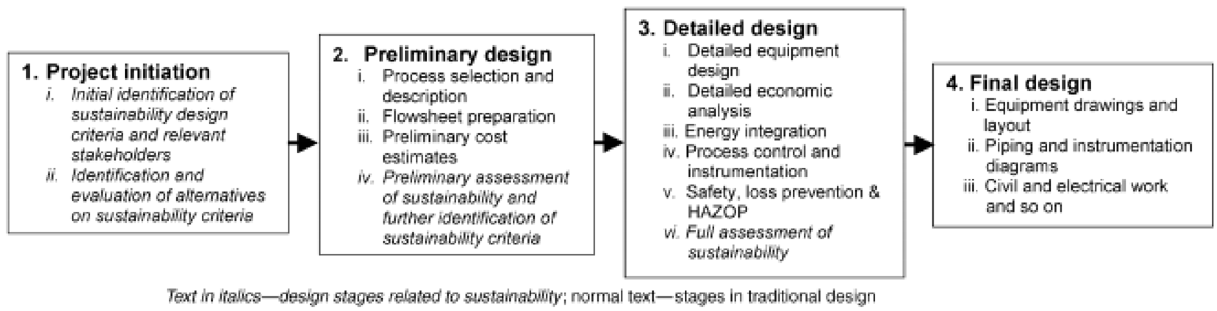

Figure 6: Stages in process design for sustainability (Azapagic, et al. 2006)

2.1.9 Tool and Metrics

Many tools have been developed based on many different methodologies. Qualitative and quantitative metrics are one common method to evaluate and improve the sustainability performance of manufacturing processes or products. The product sustainability index (ProdSI) was proposed to establish comprehensive methodology for assessing sustainability performance of manufacturing processes or products based on 6R (Zhang, et al. 2012, Shuaib, et al. 2014). Tools Based on Checklists is another qualitative tool that is the easiest to implement and is the most popular, particularly for the small or medium size company (Devanathan, et al. 2010). The checklist is a common feature of these tools and the checklist is a set of questions used to assess a product according to the environmental perspective over its entire life cycle. However, expert knowledge in the area is needed and question responses are very subjective (Ramani, et al. 2010). Another method is the tool based on Quality Function Deployment (QFD). QFD method uses a functional analysis to identify how quality characteristics correlate with engineering and environmental characteristics. Customer and environmental needs, developing correlations between these needs, and quality characteristics must be collected before using the tool. The disadvantage of this method is that the correlation is totally dependent on the designer and the correlation is built based on the traditional environmental engineering discipline (Bouchereau, et al. 2000). LCA tool is also based on ISO 14040. Life cycle assessment (LCA) is a method used to evaluate the environmental impact of a product through its life cycle, including extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal (Chiu, et al. 2012). LCA is the most objective tool available for evaluating the environmental profile of a product or process, but LCA tools need detailed information about all of the product and is very time consuming. These factors make it not very suitable in the early design stage (Haapala, et al. 2013). An eco-design tool is proposed by integrating CAD and LCA without the assistance of an environmental expert. The environmental influence of the product during all life cycle stages is analyzed with the geometric characteristics of a CAD model (Gaha, et al. 2013).

2.1.10 Summary

There is one major disadvantage of all these concepts, methodologies, and tools. Each one only focuses on evaluation and designing one product or one system at a time. Designing one product cannot satisfy all the market customers and a company will then lose in the competition. Product family is one approach that many companies can use to simultaneously satisfy customers and save costs.

2.2 Product Family Design and Platform-based Product Design

As commonly known, one product cannot fulfill all customer requirements. Manufacturing company competitiveness depends on its ability to respond quickly to all customers and to produce a variety of products at relatively low costs. Mass customization is proposed in the contemporary battlefield and aims to satisfy individual customer needs while taking advantage of mass production efficiency (Pine, 1999). Mass customization is "a new way of viewing business competition, one that makes the identification and fulfillment of the wants and needs of individual customers paramount without sacrificing efficiency, effectiveness, and low costs" (Pine, 1999).

Many companies that design one product at a time have found that the focus on individual customers and products results in competitive global marketplace failure. Manufacturers have sought the means to expand their product lines and differentiate their product offerings to fulfill different requirement of customers (Jiao, et al. 2007). In order to achieve these aforementioned goals, product family design and platform-based product development currently receives much attention. Designing and developing product families has been well recognized as an effective method to achieve the economy of scale and accommodate increasing product variety across diverse market niches (Utterback, et al. 1993).

Product family is "defined as a set of product variants each having some common components or technology" (Tyagi, et al. 2012). Two approaches are developed in platform-based product family design, module-based product family and scale-based product family (Simpson, 2004).

Module-based product family design is a top-down or bottom-up approach and all the product family members are derived by adding, substituting, and/or removing one or more functional modules (Du, et al. 2001). Module identification/modularization is the primary problem to be solved in this approach. Quality function deployment (QFD) is developed to find the right product specification. In this method, module creation, interface analysis, and module configuration are carried out with the QFD matrix (Erlandsson, et al. 1992). Modular function deployment (MFD) is created by applying the QFD matrix to modular analysis based on QFD (Erixon, et al. 1993). A concept selection techniques for managing modular product development is introduced in the early stages of design (Mattson, et al. 2001). A heuristic method is proposed to identify modules for these product architectures (Stone, et al. 1998) and another heuristic method is introduced to identify functional and vibrational modules within a product family (Zamirowski, et al. 1999). A five-step algorithm is developed to find common modules across products by grouping and creating a dendrogram (Hölttä, et al. 2003). A data mining technique is proposed for product family design with emphasis on mapping specific functional requirements in a technical structure (Agard, et al. 2004).

Scale-based product family is one approach that uses scaling variables that “stretch” or “shrink” the platform in one or more dimensions to satisfy a variety of customers in different markets (Simpson, 2004). Simpson et al. (2001) first introduced the product platform concept method by minimizing the sensitivity of performance variations in scaling factors (Simpson, et al. 2001). Two basic tasks are involved in the scale-based product family, platform selection and determination of the optimal values of common and distinctive variables (Jiao, et al. 2007). A new single-stage approach utilizing the Physical

Programming method is presented to provide a more effective approach for product family design (Messac, et al. 2002). In order to solve the tradeoff between commonality and performance within a product family, a penalty function is introduced to the selection of the right combination of common and scaling variables (Messac, et al. 2002). Sensitivity analysis is also used to derive the penalty on performance loss due to commonality (Fellini, et al. 2004).

Measuring the success of all these platforms and platform leveraging strategies is also very important. Numerous metrics have been developed to measure commonality. A simple modularity metric is proposed with the function-to-component ratio for each product (Ulrich, 1995). Another metric is developed to measure product modularity with a component-to-component matrix (Guo, et al. 2004). A quantitative metric is developed for design-by-analogy based on the functional similarity of products (McAdams, et al. 2002). Numerous commonality indices for assessing product families are also developed and compared (Thevenot, et al. 2006). Indices include Degree of Commonality (Collier, 1981), Commonality Index (Martin, et al. 1997), Percent Commonality Index (Siddique, et al. 1998), and Component Part Commonality Index (Jiao, et al. 2000).

Product family design is typically a multi-objective optimization problem. Several optimization approaches have been developed to solve the multi-objective optimization problem. A single-stage approach is proposed to enable designers to formulate the product family optimization problem in terms of physically meaningful terms and parameters with the Physical Programming method (Messac, et al. 2002). A two-stage approach is introduced to solve the computational challenges of single-stage approaches (Nelson, et al. 2001). A multistage optimization approach is developed by viewing the product platform design problem as a problem of access in a geometric space (Hernandez, et al. 2003). The Dynamic Programming model also is introduced to configure a module to maximize the total profit in a given planning horizon (Allada, et al. 2002).

A variety of optimization algorithms are also used to solve the product family optimization problem. Exhaustive search techniques and orthogonal arrays can be used to enumerate different combinations of parameter settings and modules if design space is small enough (Simpson, 2004). Both linear and non-linear programming algorithms, such as SLP, SQP, NLP and GRG, are applied in many case studies, as well as derivative-free methods including genetic algorithms, simulated annealing, pattern search, and branch and bound techniques (Jiao, et al. 2007). Simpson (2004) generated a detailed comparison of these algorithms. The comparison is shown in Figure 7.

	Formulation Details								Stages			Optimization Algorithm						
Approach	Module-Based Family	Scale-Based Family	Specify Platform *a priori*?	Single Objective	Multi-objective	Model Manufac. Cost?	Model Market Demand/ Sales	Consider Uncertainty?	Single Stage	Two Stage	Multi-stage	SLP	SQP	NLP	GA	SA	Other	Example Product Family (# Products in Family)
Allada & Jiang, 2002	x		Y	x			x	Y			x						DP	Generic modular products (3)
Blackenfelt, 2000*b*	x		Y	x		Y		Y	x								OA	Lift tables (4)
Cetin & Saitou, 2003	x				x				x						x	x		Welded automotive structures (2)
Chang & Ward, 1995	x		Y	x				Y	x								OA	Automotive A/C units (6)
D'Souza & Simpson, 2003		x	Y		x				x						x			General Aviation Aircraft (3)
Farrell & Simpson, 2003		x	Y	x			x			x							GRG	Flow control valves (16)
Fellini et al., 2000	x		Y		x					x				x				Automotive powertrain (3)
Fellini, Kokkolaras, Michelena, et al., 2002		x			x					x			x					Automotive vehicle frame (2)
Fellini, Kokkolaras, Papalambros, et al., 2002		x			x					x			x					Automotive vehicle frame (2)
Fujita et al., 1998	x		Y	x		Y	x		x				x					Commercial aircraft (2)
Fujita et al., 1999	x			x		Y			x							x		TV receiver circuits (6)
Fujita & Yoshida, 2001	x	x		x		Y	x		x				x		x		B&B	Commercial aircraft (4)
Gonzalez–Zugasti et al., 2000	x		Y		x				x					x				Interplanetary spacecraft (3)
Gonzalez–Zugasti & Otto, 2000	x			x		Y			x						x			Interplanetary spacecraft (3)
Gonzalez–Zugasti et al., 2001	x		Y			Y	x	Y		x				x				Interplanetary spacecraft (3)
Hernandez et al., 2001		x	Y		x	Y				x						x		Absorption chillers (8)
Hernandez et al., 2002		x		x							x						PatS	Universal electric motor (10)
Hernandez et al., 2003	x	x		x		Y					x						ExS	Pressure vessels (16)
Jiang & Allada, 2001	x			x		Y	x	Y		x		x						Vacuum cleaners (3)
Kokkolaras et al., 2002	x		Y		x					x				x				Automotive vehicle frame (2)
Li & Azarm, 2002	x		Y	x	x	Y	x	Y		x					x			Cordless screwdrivers (3)
Messac et al., 2002*b*		x			x					x				x				Universal electric motor (10)
Messac et al., 2002*a*		x	Y		x				x					x				Universal electric motor (10)
Nayak et al., 2002		x			x					x		x						Universal electric motor (10)
Nelson et al., 2001	x		Y		x					x				x				Nail guns (2)
Ortega et al., 1999		x			x	Y			x			x						Oil filters (5)
Rai & Allada, 2002	x				x	Y	x			x				x				Elec. screwdriver (3) & knife (4)
Seepersad et al., 2000		x	Y		x	Y	x	Y	x							x		Absorption chillers (8)
Seepersad et al., 2002		x	Y	x		Y	x	Y		x						x		Absorption chillers (12)
Simpson et al., 1999		x	Y		x				x			x						General Aviation Aircraft (3)
Simpson, Maier, & Mistree, 2001		x	Y		x					x							GRG	Universal electric motor (10)
Simpson & D'Souza, 2002		x			x				x						x			General Aviation Aircraft (3)

Note: SLP, sequential linear programming; SQP, sequential quadratic programming; NLP, nonlinear programming; GA, genetic algorithm; SA, simulated annealing; DP, dynamic programming; OA, orthogonal array; GRG, generalized reduced gradient; B&B, branch and bound; PatS, pattern search; ExS, exhaustive search.

Figure 7: Summary of engineering optimization approaches for product family design (Simpson, 2004)

It is noted that this research only considers economic and function performance during the mathematical modeling process.

2.3 Sustainability and Product Family Design

Life cycle cost issues associated with modular product architectures were first discussed in the mid-1990's (Ulrich, 1995). A decomposition algorithm was created to partition architectures into modules based on different life cycle viewpoints (Newcomb, et al. 1998). The impact of modularity on component reuse also was discussed (Kimura, et al. 2001).

This research was only about modularity and a few life cycle factors. As of yet, there has been no research examining product family and total life cycle analysis.

Some researchers have begun to consider environmental factors during product family design process. Product family design re-use (PFDR) is proposed for sustainability of product family design. A three-stage process model is proposed to manage the design processes and the information content assessment (ICA) method is proposed for product performance evaluation in (Xu, et al. 2007). A quantitative model for assessing product family design from an end-of-life perspective is proposed to identify an optimal strategy for managing product take-back and end-of-life recovery with mixed integer programming. Researchers assessed the product family design in terms of its profitability in end-of-life management (Kwak, et al. 2011). An assessment tool was also introduced to evaluate a product platform that considered a number of sustainability factors with a set of metrics (Hölttä-Otto, et al. 2006).

Despite researchers' efforts, these methods have not yielded a mathematical model to design a product with total life cycle analysis and instead only consider a few stages of life cycle analysis. In response, the research presented in this thesis will yield a proposed mathematical model tool for considering all the stages of the total life cycle in product platform design process to address deficiencies through integration of LCA software and ProdSI.

3. Methodology

The objective of this research is to develop a mathematical tool that can assist the designer in choosing the best combination of components to design a product family and to determine the best platform. Economic, environmental, and societal factors will be considered across all four life-cycle stages at the same time. The key characteristic of the product family in a platform based design is component sharing between different products in the family. One product family has multiple products and one product has multiple components with each component also having multiple options (See Figure 8). The mathematical model must assist in choosing the best combination of components and aid in determining the components that can be shared between products through optimization based on the data relevant to all stages of the life-cycle. This section will describe the methodology used to identify sustainability metrics and how to quantify them in designing sustainable product family and identifying shared components.

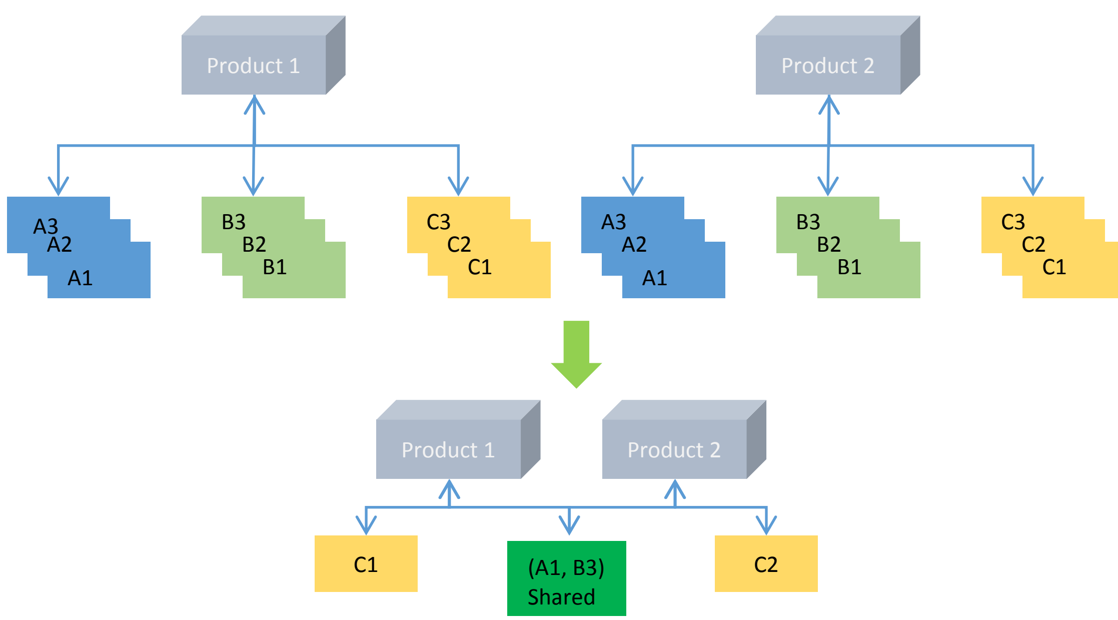

Figure 8: Platform-based Product Configuration

Several steps need to be completed to develop the mathematical tool. First, the closed-loop material flow structure must be defined. All the metrics required for economic, environmental, and societal product sustainability evaluation are identified according to the material structure. Metrics are also identified for all stages of the life-cycle to provide a total life-cycle sustainability assessment. Four tasks are proposed to calculate the sustainability metrics for sustainable product family design and component sharing. LCA software, SimaPro, is used to quantify environmental metrics, CO_2 emissions, and energy consumption, and all the data from SimaPro will be utilized in the next step. A methodology to calculate a customer satisfaction index also is proposed based on different market segments. An empirical function is proposed to measure disassemblibility and service in order to capture the impact of this key characteristic in product family design. A learning curve is considered to calculate manufacturing cost, as sharing more components will reduce manufacturing time. Nearly of these factors have different units of measurement. Therefore, normalization is a necessary step after the metrics are quantified. Analytic Hierarchy Process (AHP) will be deployed to calculate the weight of different metrics. A multi-objective optimization problem is identified and a mixed integer linear programming model is formulated to find the best combination of components and identify component sharing. ILOG OPL optimization software will be used to solve this multi-objective optimization problem and identify the platform and most sustainable product family design. Comparison of regular and sustainable product platform configuration design will then be studied. The following figure shows detailed information for the methodology (See Figure 9). Each of the steps are described in detail in the following sections.

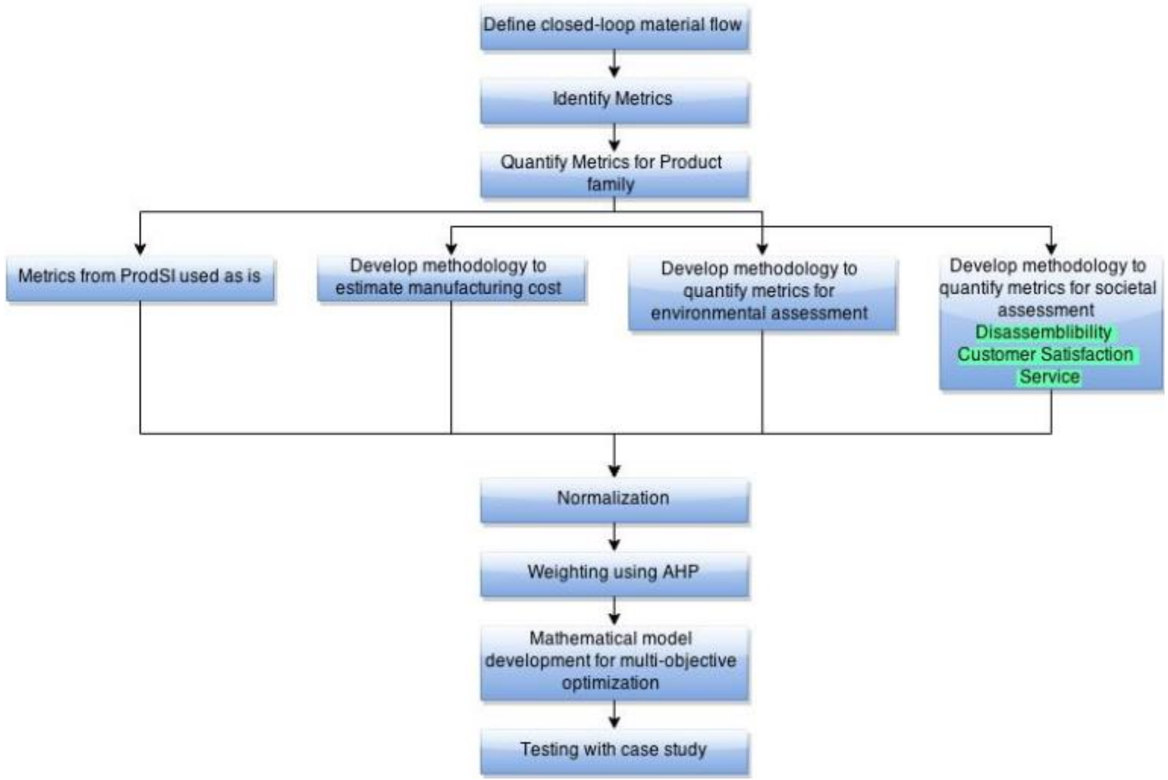

Figure 9: Steps for developing the Decision Support Tool

3.1 Defining Closed-loop Material Flow Structure

In order to identify closed-loop material flow, all material included in the four stages of life cycle, which include pre-manufacturing, manufacturing, use, and post-use must be considered (See Figure 10).

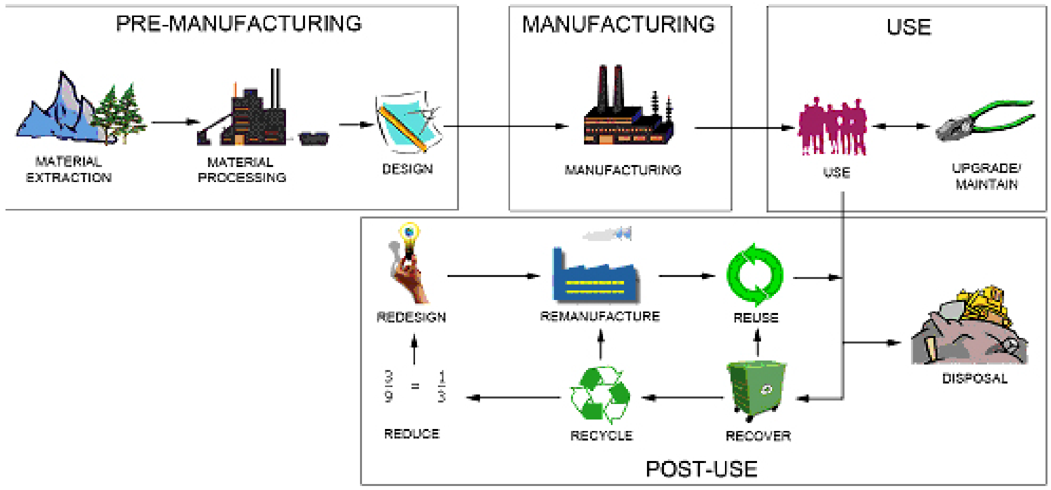

Figure 10: The closed-loop product life-cycle system for material flow (Jaafar, et al. 2007)

The pre-manufacturing stage includes raw material extraction and preliminary material manufacturing processes. Raw material costs need to be paid after receiving the order from the factory. CO_2 emission and energy consumption will be generated during the pre-manufacturing stage. The raw material must be transported to the factory for further manufacturing. Manufacturing stage include component manufacturing and component assembling for the final product. Raw materials need specific manufacturing processes (e.g., milling, cutting, etc. to become components). The product is manufactured after all components are assembled together. Many types of machines, labor, and energy will be necessary for this process, while CO_2 emission, energy consumption also will be generated. Use stage includes all the activities involved in product use after the customer has received the product. All of the economic, environmental, and societal factors that impact this stage need to be incorporated into the model. The post-use stage includes recycling and remanufacturing of the used product. Some percentage of products can be reused again if the product is at the end of life stage and collected by OEM. However, it is not possible for all of the components remanufactured or to be recycled for material. This work will set a recycling coefficient to decide how much material can be recycled and remanufactured. The company also will earn revenue and save costs with recycling. Once the closed-loop material flow is defined, all the major activities happening in the material flow will be considered in the model and will be quantified with metrics. Detailed information about these metrics will be introduced in the following section.

3.2 Identifying Metrics

Sustainability is an interdisciplinary research area which considers economic, environmental and societal factors by focusing on the dynamic interactions between nature and society (Clark, et al. 2003). The Product Sustainability Index (ProdSI) methodology is developed by identifying a comprehensive set of product sustainability metrics that incorporate the four product life-cycle stages and include the 6R application (Shuaib, et al. 2014). Wijekoon (2011) also identified a list of metrics to evaluate sustainability factors for Product Service Systems across all stages of the total life-cycle. However, these metrics are for evaluation of a single product or component. One product family includes multiple products and many components can be shared between those products. The evaluation metrics should capture the influence on sustainability when components are shared. This work will modify these metrics to adapt them for sustainability evaluation of the product family. However, some evaluation metrics are very difficult to incorporate in component sharing (e.g., energy cost, raw material cost, and recyclability). Some metrics from ProdSI are utilized directly in the evaluation of product family sustainability.

Once all economic, environmental, and societal metrics of the product family are built in across all stages, the total life-cycle sustainability evaluation of product family can be done. According to the Closed-loop Material Flow Structure which is defined in Section 3.1, the most important metrics are considered and the list of metrics selected to evaluate sustainability is shown in the following table (See Table 1). The relevant 'R' covered by the metric is also identified.

Table 1: The Metrics for Product Family Evaluation

	Metric	PM	M	U	PU	6R
Economic	Labor Cost	X	X		X	Reduce
	Energy Cost	X	X	X	X	Reduce
	Raw material Cost	X	X			Reduce, Reuse, Redesign
	Facilities Cost	X	X		X	Reduce, Reuse
	Design and Development Cost		X			Reduce, Redesign
	Revenue from recycle	X			X	Reduce, Reuse, Recycle, Remanufacture
Environmental	Energy Consumption	X	X	X	X	Reduce
	CO2 Emission	X	X	X		Reduce
Societal	Recyclability				X	Reduce, Reuse, Recycle, Remanufacture
	Service			X	X	
	Disassemblibility				X	Reduce, Reuse, Recover, Recycle
	Safety	X	X	X		Reduce
	Customer Satisfaction			X		

3.3 Quantifying metrics

In order to consider the influence on sustainability performance when more components are shared, this work will try to consider all the metrics as a function of components variability or the number of components shared between products. As a result, the evaluation of each metric will be changed as component sharing is changed and further influences sustainability performance.

Manufacturing cost will be less if more components are shared because workers will be more familiar with manufacturing process. Facility costs, and design and development costs also will be less as more components are shared because less machines will be needed. Because CO_2 emission and energy consumption are primary factors that influence global warming, this work only include CO_2 emission and energy consumption in the evaluation of environmental impact. Yet, the relationship between energy cost, raw material cost, revenue from recycling, and component sharing are unknown at this time. The relationship between CO_2 emissions, energy consumption, and components sharing is also unknown. This work will use LCA software to calculate CO_2 emissions and energy consumption of the product family and does not consider component sharing in the evaluation of CO_2 emissions and energy consumption. The service and disassemblibility of the product will be improved because of repeated work from component sharing. Each product needs different machines in the pre-manufacturing and manufacturing stages and the safety of workers in machine operations is a major concern. Sharing components can reduce the total number of machines used in the work involved and, as a result, safety will be improved. The relationship between recyclability, customer satisfaction and component sharing is unknown and warrants further study. This work will directly use ProdSI and CSI to measure the recyclability and customer satisfaction of the product family design. The relationship between these metrics and components sharing is showed in Table 2. Detailed information of the methodology is presented in the following section.

Table 2: Metrics and Influence Due to components sharing

	Metric	Sharing Components
Economic	Labor Cost	Reduced
	Energy Cost	Exact relationship not known yet
	Raw material Cost	Exact relationship not known yet
	Facilities Cost	Reduced
	Design and Development Cost	Reduced
	Revenue from recycle	Exact relationship not known yet
Environmental	Energy Consumption	Exact relationship not known yet
	CO2 Emission	Exact relationship not known yet
Societal	Recyclability	Exact relationship not known yet
	Service	Increase
	Disassemblibility	Increase
	Safety	Increase
	Customer Satisfaction	Exact relationship not known yet

3.3.1 Developing Methodology to Estimate Manufacturing Cost

One major part of overall cost comes from manufacturing processes. Components require all types of machines for fabrication, labor is needed to operate these machines, and energy is consumed. The total manufacturing cost will include facility cost, labor cost, and energy cost. Fewer machines will be needed if more components are shared and facility cost can be saved. As commonly known, the cumulative average direct labor cost per unit will decrease as production volume increases. The decrease is caused by increased operator proficiency as they perform various repetitive tasks (Kar, 2007). As a result, labor cost savings are present when more components are shared. The learning curve can capture what happens to labor cost when more components are shared in the product family. The exponential function for the learning curve is described as follows (Grant, 2010):

$$C_n = C_1 n^{-a} \tag{1}$$

Where: C_1 is the cost of the first unit of production, C_n is the cost of the n^{th} unit of production, n is the cumulative volume of production, and a is the learning rate of production. In order to simplify the model, a linear learning curve will be used:

$$T = A - B * N \tag{2}$$

Where T is the average production time of each component, N is the total number of components that need to be produced, A, B are the coefficients of the linear learning curve. A, B can be obtained from the performance records based on labor times used for previous product. but A, B are assumed here due to lack of data.

3.3.2 Developing a Methodology to Quantify Metrics for Environmental Assessment

In examining environmental impact, CO_2 emissions and energy consumption of the production process significantly impacts global warming. Each component requires different manufacturing processes for fabrication and assembly of the final product. They each need energy which results in CO_2 emissions. Detailed information for each manufacturing process must be collected in a comprehensive evaluation of CO_2 emissions and energy consumption. But because manufacturing processes are different across companies, accurate CO_2 emission data is difficult to collect. As a result, there is very little data that can be used to make an evaluation of CO_2 emissions and energy consumption. Life cycle software, such as SimaPro, can provide CO_2 emission and energy consumption data for some standard manufacturing processes. LCA software will be used in this study to compute CO_2 emissions and energy consumption for the manufacturing processes in the product family studied.

The manufacturing processes required for components will be identified based on process flow (Such as shown in Figure 11) and the corresponding flow will be incorporated into SimaPro. The output will be generated by selecting the manufacturing process in the SimaPro database and using it to calculate the CO_2 Emission and Energy consumption for each manufacturing process required for the product being studied. An example output from SimaPro is shown in Figure 12, where the amount of raw materials that will be required in each manufacturing step to produce 1kg of component is shown. An example of numerical data that can be derived from the flow chart is shown in Figure 12 and Table 3. All data from SimaPro will be used for environmental impact evaluation and will be imported into the mathematical model (See Table 3). All available components in the product design will be evaluated in SimaPro, and CO_2 emission and energy consumption data will be generated from SimaPro.

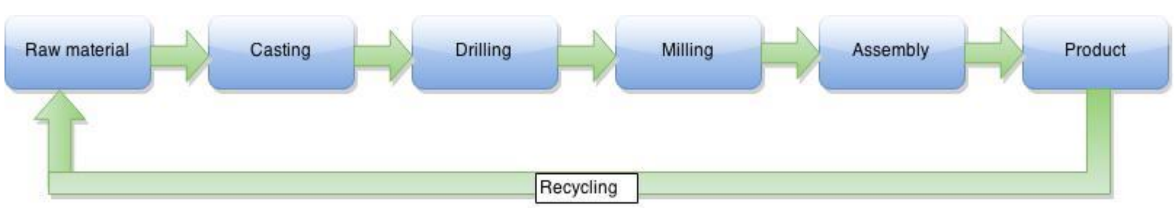

Figure 11: Example Manufacturing Process for a Component

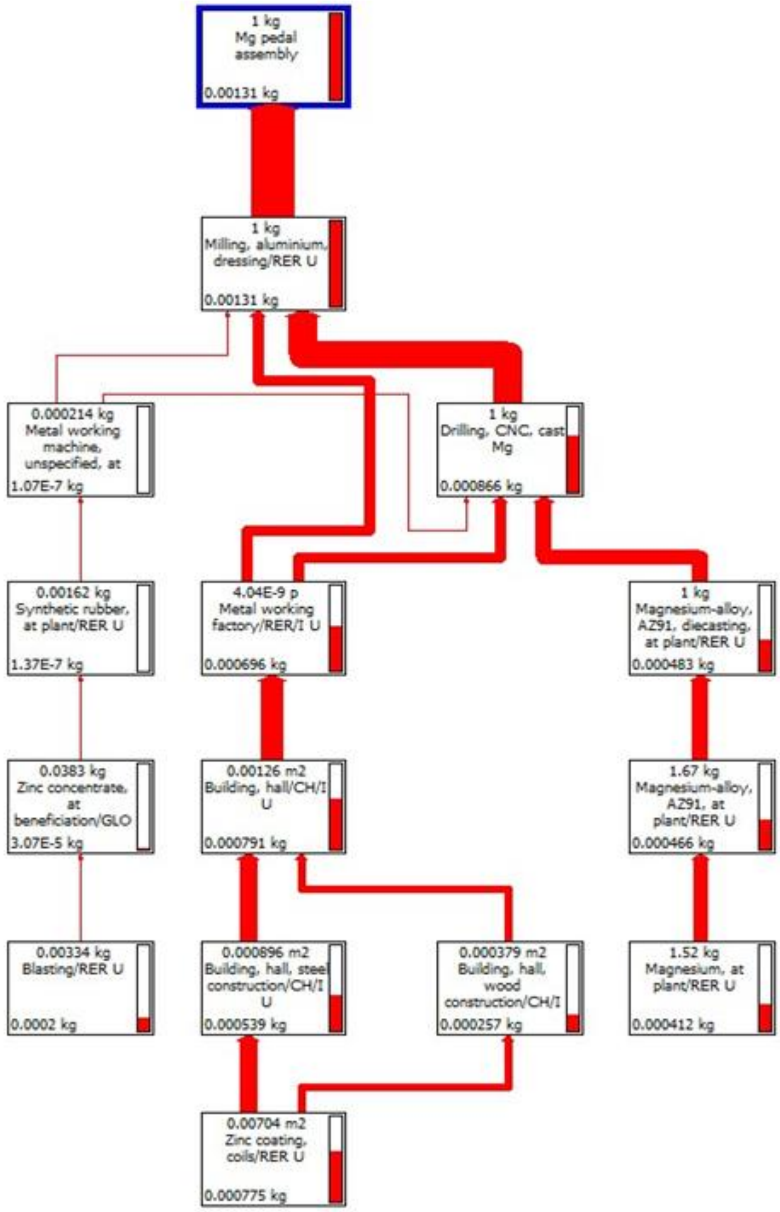

Figure 12: Example Output of SimaPro

Table 3: Example SimaPro Data Export

126	Carbon dioxide, biogenic	Air	oz	36.8
127	Carbon dioxide, fossil	Air	oz	131
128	Carbon dioxide, in air	Raw	g	121
129	Carbon dioxide, land transformation	Air	mg	111
214	Energy, gross calorific value, in biomass	Raw	Wh	349
215	Energy, gross calorific value, in biomass, primary forest	Raw	J	40.9
216	Energy, kinetic (in wind), converted	Raw	kJ	219
217	Energy, potential (in hydropower reservoir), converted	Raw	Wh	447
218	Energy, solar, converted	Raw	kJ	3.23

3.3.3 Developing Methodology to Quantify Societal Assessment

3.3.3.1 Service and Disassemblibility

Service, which mainly includes repair of the damaged product/dysfunctional product, is one of the most important factors in determining if a product will succeed in the market. Customers will be more likely to come back for a product if the service is excellent. Service. Quality of serve is determined by how quickly the service department can respond to the customer and how quickly the repaired product is returned. With product family design, one product family can potentially have multiple products. Sharing components between the products will make the service staff more familiar with the products and repair work can be completed faster. This assumption also holds true for disassemblibility. Sharing components will make disassembly simpler and the operator will be more familiar with the disassembly process so that less machine time will be needed and efficiency will be improved.

In order to capture the impact of component sharing on service and disassemblibility, an empirical function is introduced. The empirical function will be a function of component variability in the product family. The method for calculating the empirical function is as follows. Assume that there are two scenarios for the quality of service. First, we assume service will be worst if there is no component sharing between completely customized products. The employees in the service department will need more time to figure out how to repair such products and they will need a larger knowledge base to handle a greater number of components. The service coefficient will be set to 0 in this case. Second, we assume service will be the best if all components are shared with only one product in the product family. The employees will be very familiar with all components, and will need less time to repair the product. The employees will be easily trained and a larger knowledge base is not needed. The service coefficient will be set to 1 in this case.

In order to simplify the model, a linear empirical function is assumed to quantify the above relationship: $SE = a + b * x$. The function can be solved based on the two scenarios described above where a and b can be found.

$$a + b * X_{max} = 0 \quad (3)$$

$$a + b * X_{min} = 1 \quad (4)$$

Where, X_{max} is the maximum possible component variability in the product family, $X_{min}$is the minimum possible components variability in the product family and a and b are the coefficient of the empirical function.

The same approach is followed to obtain the disassemblibility empirical function. Even if there is only one product in the product family, it will still take some time to disassemble all of the product so 0.9 assumed for this best case scenario and 0.1 is assumed for the worst case scenario. When more components are shared, the disassemblibility will be higher.

$$c + d * X_{max} = 0.1 \quad (5)$$

$$c + d * X_{min} = 0.9 \quad (6)$$

Where c and d are the coefficient of the disassemblibility empirical function.

3.3.1.2 Customer Satisfaction

Customer satisfaction is also one of the most important factors for societal sustainability. More customers will buy a product when satisfaction is high. Many criteria have been developed to measure customer satisfaction. Wijekoon (2011) proposed a Customer Satisfaction Index (CSI) to distinguish between customer satisfaction performance for different product options. However, this method can only measure customer satisfaction for one product, not a product family based on a platform. A new method is proposed to measure customer satisfaction for multiple products based on CSI. This work will not focus on criteria, but will examine how to use CSI to measure customer satisfaction for multiple products.

Multiple products (P1, P2, and P3) will be included in one product family. Let's assume each product meets the requirements of customers in one specific market segment (Market 1, Market 2, and Market 3). P1 meets the requirement of Market 1, P2 meets the requirement of Market 2, and P3 meets the requirement of Market 3 (See Table 4). Several options (O11, O12… O1i) are available for each component (C1). So customer satisfaction is different for the same component option (for example, O11) between different products (P1, P2, and P3) in different markets (Market 1, Market 2, and Market 3) (See Table 4). CSI measures each components option based on different products in different markets. After all the customer satisfaction data is collected with CSI criteria, the information will be used in the mathematical model.

Table 4: Customer satisfaction for different market

Market	Product	C1				C2				C3				…
		O11	O12	…	O1i	O21	O22	…	O2i	O31	O32	…	O3i	…
Market 1	P1	4	7		9									
Market 2	P2	6	4		3									
Market 3	P3	2	1		6									

3.4 Normalization

All these metrics must be added together after the data is collected. However, the units of measurement for the metrics are not the same, and they cannot be added together directly. Thus they must be converted into unitless quantities. This work proposes to use the data from a prior product as the baseline to normalize the metrics. One example is shown below.

$$C_{new} = \frac{C}{C'} \tag{7}$$

Where, C is the cost of a new product family, C' is the cost of the baseline product, and C_{new} is the unitless measure for the cost. Normalization interpretation yields how much the cost of a new product family improves compared to the old product. For example, the cost will be reduced by 20% if C_{new} is 0.8, and the cost will increase 20% if C_{new} is 1.2. The same method will be used for all the other metrics that have different units.

3.5 Weighting with AHP

The normalized metrics still cannot be added together directly after the normalization process. Different metrics have diverse impact on product sustainability performance, which can also vary depending on the industry. Some industries have high energy consumption and pollution that requires more weight be given to environmental metrics during sustainability evaluation in the early design process for reducing environmental impact. For example, environmental metrics play a key role in the sustainability evaluation of the chemical industry, while they may not be as important in the service industry. Determining the relative weight must be amplified. This work will propose a method to obtain the relative weights of the metrics for product platform design.

The Analytic Hierarchy Process (AHP) is an effective and efficient method for choosing the best decision in a set of competing alternatives evaluated under conflicting criteria (Saaty, 1986). AHP method can be used to obtain priority importance of variables by making a series of paired comparisons. In this research, all criteria that must be considered for sustainability evaluation will be compared pair-wise to assign a number, as shown in Table 5. A basic assumption of this method is that if attribute A is absolutely more important than attribute B and is assigned a number at 9, then B must be absolutely less important than A and is valued at 1/9.

Table 5: AHP Pairwise Comparison Scale

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

AHP results rely on the expertise of the person who conducted the comparison. To obtain more precise results, the comparison should be conducted with multiple experts in the area. Assume there are four criteria that are going to be compared (See Table 6). A questionnaire will be sent to each expert separately comparing two criteria at a time and they will choose a number according to Table 5 to rate relative importance.

Table 6: Questionnaire for Expert

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
criteria 1																		criteria 2
criteria 2																		criteria 3
criteria 3																		criteria 4
criteria 4																		criteria 1
criteria 2																		criteria 4
criteria 1																		criteria 3

Pair-wise comparisons will be put into a matrix and the weights will be calculated through the eigenvector method (See Table 7). There are many methods for calculating eigenvector. Multiplying together the entries in each row of the matrix and then taking the n^{th} root of that product gives a very good approximation of the correct answer (Saaty, 1986). Then the n^{th} roots are summed and the sum is used to normalize the eigenvector elements. The normalized eigenvector is the weight needed. The detailed process of this calculation is shown in Table 7. The relative importance of each criteria is obtained by dividing the n^{th} root of the product of values corresponding to that criteria by the sum of the same values for all the criteria, as shown in Table 7.

Table 7: The calculation of AHP Weight

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	n^{th} root of product of values	Eigenvector
Criteria 1	1	a	b	c	$\sqrt[4]{1*a*b*c}$	$\sqrt[4]{1*a*b*c}/_{sum}$
Criteria 2	1/a	1	d	e	$\sqrt[4]{(1/a)*1*d*e}$	$\sqrt[4]{(1/a)*1*d*e}/_{sum}$
Criteria 3	1/b	1/d	1	f	$\sqrt[4]{(1/b)*(1/d)*1*f}$	$\sqrt[4]{(1/b)*(1/d)*1*f}/_{sum}$
Criteria 4	1/c	1/e	1/f	1	$\sqrt[4]{(1/c)*(1/e)*(1/f)*1}$	$\sqrt[4]{(1/c)*(1/e)*(1/f)*1}/_{sum}$
Totals					Sum	

3.6 Multi-objective Optimization

The total life-cycle sustainability evaluation includes metrics for the economic, environmental, and societal evaluations of the product family design. The target is to increase economic and societal benefit, reduce environmental impact, and identify the components that can be shared in the platform at the same time. This target could be achieved by multi-objective optimization.

Different methods can be used in the multi-objective optimization problem. The weighted sum is one of the simplest and most widely used classical methods. This method can aggregate a set of objective functions by multiplying each objective function with a user decided weight to obtain a single objective function. In this research, a weighted sum method will be used to solve the multi-objective optimization problem. The weighted sum method can be formulated as follows:

$$G = \sum_{i=1}^{n} w_i \, O_i \tag{8}$$

$$\sum_{i=1}^{n} w_i = 1, \qquad w_i \geq 0 \tag{9}$$

Where G is the final objective function value, n is the number of objective functions in the set (n is 3 in this case) and w_i is the relative weight of objective function O_i.

A mixed integer linear programming (MILP) model will be developed to formulate the multi-objective problem. ILOG OPL optimization software will used to solve this optimization problem. The detail mathematical model will be introduced in the next section.

4. Mathematical model

4.1 Problem Statement

This work proposes a model for identifying platform-based product configuration from a total life-cycle sustainability perspective. The proposed model is summarized according to the following optimization problem:

(1) Given:

- The number of market segments needed to fulfill the requirements of all customers
- All the information for available components that can be used in the product family
- Manufacturing processes for all the components and all the equipment needed
- Costs of raw material, design and development cost for every component, and cost of all equipment
- Labor time required for every component, coefficient of the learning curve, and empirical functions
- Customer satisfaction index and safety coefficient for every machine

(2) Determine:

- Optimal combination of components to achieve sustainability of the product family
- The shared components in the product family

(3) Subject to:

- The functional performance of products fulfilling the requirements of the market segment
- Environmental regulations: CO_2 emission and energy consumption target
- Variable condition: binary variable

- Component combination: some components cannot be assembled together

(4) The objective

- Maximizing total life-cycle sustainability of the product family

The model assumption and notations will be presented in the following sections to explain all equations in extensive detail.

4.2 Cost Estimation

4.2.1 The Cost of Raw Material

Raw material is a common cost in the production of a specific product. The cost of raw material, CR, for this product family includes the raw materials cost for all the components used for all the products in the family. Every product needs different components, so one combination of different components must be chosen. In order to calculate the total cost of raw materials, the total number of products needed in each market will be collected. The weight of every chosen component, W, and the cost per unit weight for this component, C, also must be calculated as the total cost of raw material. The total raw material cost will be estimated with the following formula. CR_{c_k} is the cost of raw material for component c_k and is calculated in Equation (10). CR is the cost of material for the total product family and is calculated in Equation (11).

$$CR_{c_k} = \sum_{i=1}^{np} (N_i \cdot (\sum_{j=1}^{n_k} b_{c_k,i,j} \cdot W_{c_k,j} \cdot C_{c_k,j})) \tag{10}$$

$$CR = \sum_{c_k=1}^{nc} CR_{c_k} \tag{11}$$

Where np is the total number of products in the family, n_k is the total number of alternates for component c_k, nc is the total number of components needed to make one product, N_i is the number of unites of product *i* needed to satisfy all customer demands in the market segment i, $W_{c_k,j}$ is the weight of alternate j for component $c_k$and $C_{c_k,j}$ is per unit raw material cost of alternate j for component c_k . $b_{c_k,i,j}$ is the binary variable represented if option *j* of component C_k will be chosen in product i.

4.2.2 The Cost of Design and Development

It is assumed that the design and development cost of all the components is known. Design and development cost needs to be paid if a certain component is chosen, because a professional engineer is needed to design the component. The design and development costs vary because of different designing times for components. When components are shared in the product family, design cost will be less due to fewer components being designed. Take one component c_k for example, the design and development cost of component c_k will be calculated with Equation (12), and the total design and development cost of the product family is estimated by Equation (13).

$$Codd_{c_k} = \sum_{j=1}^{n_k} (b_{c_k,1,j} \cup .. b_{c_k,np,j}) \cdot Codd_{c_k,j} \quad (12)$$

$$Codd = \sum_{c_k=1}^{nc} Codd_{c_k} \quad (13)$$

Where n_k is the number of choices for components c_k, np is the number of products in the family. $Codd_{c_k}$ is the design and development cost of components c_k, $Codd_{c_k,j}$ is the design cost of alternate j for component c_k , and $Codd$ is the total design and development of the product family.

4.2.3 Facilities Cost

Most production takes place in high volume production systems. It is assumed that equipment can be shared in the manufacturing of same components and that sharing equipment between different components is not allowed to simplify the flow of material. Equipment can be shared if the same kind of component is produced in the production line. The facility cost is estimated by the following formula. $bm_{c_k,i,k}$ represents if the k^{th} machine will be chosen to make the product i and is calculated with Equation (14), $CE_{c_k,k}$ is the per annum cost of the k^{th} machine to make the component c_k and is estimated with Equation (15). CF is the facilities cost of the product family and is calculated with Equation (16).

$$bm_{c_k,i,k} = \sum_{j=1}^{n_k} b_{c_k,i,j} \cdot bb_{c_k,j,k} \tag{14}$$

$$CF_{c_k} = \sum_{k=1}^{n_{k,m}} CE_{c_k,k} \cdot (bm_{c_k,1,k} \cup .. bm_{c_k,cp,k}) \tag{15}$$

$$CF = \sum_{c_k=1}^{nc} CF_{c_k} \tag{16}$$

Where $bb_{c_k,j,k}$is represented if the k^{th} machine will be chosen to make the choice j of component c_k, $n_{k,m}$ is the number of machines needed to make components $c_k$in the family,

4.2.4 The Cost of Processing

The cost of Processing CP is composed of labor cost LC and energy cost EC.

Labor cost: It is assumed that the cost of labor per hour is known. Each component has different manufacturing processes and equipment. The total manufacturing time of each component can be obtained from the manufacturing process of the component. However, when workers produce a large number of products, the time to produce one product will differ based on the learning curve. Sharing components means that more of the same component will be produced, so it will save time and labor costs. In order to simplify the model, it is assumed that the learning curve is a linear function. This learning curve will be estimated for each factory according to production data of the factory. Take a component c_k, for example. Learning curve for component c_k:

$$T = B - A * N \tag{21}$$

Where *A*, *B* are the coefficient of the learning curve, *N* is the number of components that will be produced. $LC_{c_k,j}$ is the labor cost for the alternate j of component c_k and is calculated with Equation (22). $LC_{c_k}$is the labor cost for component c_k and is calculated with Equation (23). *LC* is the total labor cost for the family and is estimated with Equation (24).

$$LC_{c_k,j} = (B_{c_k,j} - A_{c_k,j} \cdot (\sum_{i=1}^{np} b_{c_k,i,j} \cdot N_i)) \cdot (\sum_{i=1}^{np} b_{c_k,i,j} \cdot N_i) \cdot LCH \tag{22}$$

$$LC_{c_k} = \sum_{j=1}^{n_k} LC_{\,c_k,j} \tag{23}$$

$$LC = \sum_{c_k=1}^{nc} LC_{c_k} \tag{24}$$

Where, LCH is the labor cost per hour, n_k is the number of alternates for component c_k.

Energy cost: Energy will be needed when operating machines to convert raw material and manufacturing components. It is assumed that the cost of energy per unit is known and the energy will only be used in the conversion of raw material and the production process. The relationship between component sharing and energy cost is unknown yet, so this work will not consider component sharing when energy cost is calculated. The estimate of energy cost will be calculated with Equation (25) and the total cost of processing will be estimated with Equation (26).

$$EC = Ene \cdot ECH \tag{25}$$

Where ECH is the cost of energy per unit. The calculation of Ene is described in the following paragraph. Cost of processing can be obtained after add EC and LC together.

$$CP = EC + LC \tag{26}$$

4.3 Environmental Metrics Calculation

4.3.1 CO_2 Emission and Energy Consumption

The relationship between components sharing and CO_2 emission and energy consumption is unknown. It is assumed that component sharing does not affect the total environmental impact. CO_2 emission and energy consumption of the product family will be attained through adding the CO_2 emission and energy data of all the components, which will be obtained from SimaPro.

Take one component c_k, for example. The CO_2 emission and energy consumption of component c_k will be estimated from Equation (27) and (29) by adding all the data of the chosen component for each product. The total CO_2 emission and energy consumption of the product family is obtained from Equation (28) and (30) by adding the data of all the components together.

$$COE_{c_k} = \sum_{i=1}^{np} \sum_{j=1}^{n_k} b_{c_k,i,j} \cdot W_{c_k,j} \cdot COEr_{c_k,j} \cdot N_i \tag{27}$$

$$COE = \sum_{c_k=1}^{nc} COE_{c_k} \tag{28}$$

$$Ene_{c_k} = \sum_{i=1}^{np} \sum_{j=1}^{n_k} (b_{c_k,i,j} \cdot W_{c_k,j} \cdot Ener_{c_k,j} \cdot N_i) \tag{29}$$

$$Ene = \sum_{c_k=1}^{nc} Ene_{c_k} \tag{30}$$

Where COE_{c_k} is CO_2 emission of component $c_k$in this product family, $COEr_{c_k,j}$ is per unit CO_2 emission of choice j of component c_k, Ene_{c_k} is energy consumption of component c_k, $Ener_{c_k,j}$ is per unit energy consumption of choice j of component c_k.

4.4 Societal Metrics Calculation

In this work, customer satisfaction, service, safety, disassemblibility, and recyclability will be considered to evaluate societal sustainability of the product family. The reason for considering each of these metrics and how they are calculated is explained in detail in the following section.

4.4.1 Customer Satisfaction Index Estimation

The customer in different market segmentations will have different expectations for the same product. As a result, the customers of different markets will have different levels of customer satisfaction for the same components. The customer satisfaction index will be set to every component in different markets according to CSI criteria (Wijekoon 2011). The satisfaction coefficient will be a number from 0 to 10. 0 means totally unsatisfied, while 10 means totally satisfied. So the customer satisfaction metric for the total product family will be obtained with Equation (31) through adding the customer satisfaction index of all the components and normalization process. CS_{c_k} is total customer satisfaction of component c_k in the product family and is calculated with Equation (31). CS is total customer satisfaction of the product family and is estimated with Equation (32).

$$CS_{c_k} = \sum_{i=1}^{np} \sum_{j=1}^{n_k} b_{c_k,i,j} \cdot CS_{c_k,i,j} \cdot N_i \tag{31}$$

$$CS = (\sum_{c_k=1}^{nc} CS_{c_k})/(nc \cdot 10 \cdot \sum_{i=1}^{np} N_i) \tag{32}$$

Where $CS_{c_k,i,j}$ is satisfaction coefficient of choice j of component c_k for product i.

4.4.2 Service Metric Estimation

Service includes the maintenance and repair of the product. When more components are shared, it will be easier to repair the product and our service will be improved. It is assumed that the service metric can be represented with a linear empirical function, which can be summarized from the service record. Empirical function is a function of component variety of the product family. The service metric can be estimated by Equation (35) after considering components variability of the product family (Equation (34)).

$$CN_{c_k} = \sum_{j=1}^{n_k} (b_{c_k,1,j} \cup .. b_{c_k,np,j}) \tag{33}$$

$$CN = \sum_{c_k=1}^{nc} CN_{c_k} \tag{34}$$

$$SE = \alpha - \beta \cdot CN \tag{35}$$

Where CN_{c_k} is the component variety of component c_k, CN is the component variety of the total product family, α and β are coefficient of service empirical function, SE is the service ratio.

4.4.3 Safety Metric Estimation

It is assumed that the safety of factory workers is only considered in the safety metric. When the workers in the factory operate the equipment to produce components, different equipment have different safety coefficients, because some equipment is more challenging to operate which leads to more accidents. The safety coefficient of all the equipment in the factory will be obtained from history records. The safety coefficient is set as a scale from 0 to 9, 9 meaning totally safe and 0 meaning totally unsafe. The total safety will be less when more components are shared because fewer machines will be needed.

SA_{c_k} is the total safety coefficient of a machine to make component c_k and is calculated with Equation (36). SA is the safety ratio of the product family and is estimated with Equation (37).

$$SA_{c_k} = \sum_{i=1}^{np} N_i \cdot (\sum_{j=1}^{n_k} (b_{c_k,i,j} \cdot \sum_{k=1}^{n_{k,m}} (bb_{c_k,j,k} \cdot SA_{c_k,k}))) \quad (36)$$

$$SA = (\sum_{c_k=1}^{nc} SA_{c_k}) / (\sum_{i=1}^{np} N_i \cdot (\sum_{k=1}^{nc} n_{k,m}) \cdot 9) \quad (37)$$

4.4.4 Disassemblibility Metric Estimation

When sharing components, workers will be more familiar with similar products, so it will take less time to disassemble, repair, and recycle them. It is assumed that the empirical function of disassemblibility is also related to component variety of the product family and is a linear function. The disassemblibility will be obtained with Equation (38).

$$DA = \mu - \nu \cdot CN \quad (38)$$

Where μ and ν are coefficient of disassemblibility empirical function, SE is the service ratio.

4.4.5 Recyclability Metric Estimation

Some components can be recycled after disassembling the product. Different components are made of different materials, so components will have different recyclability. A number will be assigned to each component from 0 to 1, where 1 means it can be totally recycled and 0 means it cannot be recycled, according to the property of the material of the component. RE_{c_k} is the total recyclability of components c_k in the product family and is calculated with Equation (39). RE is the total recyclability of the product family.

$$RE_{c_k} = \sum_{i=1}^{np}\sum_{j=1}^{n_k}(b_{c_k,i,j} \cdot RE_{c_k,j} \cdot N_i) \tag{39}$$

$$RE = (\sum_{c_k=1}^{nc} RE_{c_k}) / (nc \cdot \sum_{i=1}^{np} N_i) \tag{40}$$

4.4.6 Revenue from Recycling

Some component can be reused again after the product is recycled, and some revenue can be obtained from the recycling. It is assumed that all the recycled material can be reused again. The total revenue of recycling will be the total cost of the recycled components. RR_{c_k} is the recycle revenue of component c_k and is calculated with Equation (41). RR is the recycle revenue of the total family and is estimated with Equation (42).

$$RR_{c_k} = \sum_{i=1}^{np}\sum_{j=1}^{n_k}(b_{c_k,i,j} \cdot RE_{c_k,j} \cdot W_{c_k,i,j} \cdot C_{c_k,i,j1} \cdot N_i) \tag{41}$$

$$RR = (\sum_{c_k=1}^{nc} RE_{c_k}) \tag{42}$$

4.5 Constraints

Function performance range: In order to fulfill requirements of the market segment, the function performance of each product must be in the performance range of every market segment. The function performance must be satisfied in order to fulfill the requirements of all customers in each market segment.

$$\sum_{c_k=1}^{nc}(\sum_{j=1}^{n_k}(b_{c_k,i,j}\cdot FP_{c_k,j})) < FPM_{i+1}, \forall\ i \in I \tag{43}$$

$$\sum_{c_k=1}^{nc}(\sum_{j=1}^{n_k}(b_{c_k,i,j}\cdot FP_{c_k,j})) \geq FPM_{i}, \forall\ i \in I \tag{44}$$

Where FPM_{i+1} is the upper limit of function performance of the market segment, FPM_i is the lower limit of function performance of the market segment. $FP_{c_k,j}$ is the function performance ratio of alternate *j* for component c_k.

Environmental regulation: Environmental regulations must be satisfied to fulfill the requirements of environmental law across countries. This constraint is represented by the regulation on CO_2 emission and energy consumption. The proposed model set a target α for the manufacturing company, which means that the new product platform must reduce $\alpha\%$ of CO_2 emission and energy consumption as compared to an existing product family.

$$COE \leq (1-\alpha\%)\cdot COE' \tag{45}$$

$$Ene \leq (1-\alpha\%)\cdot Ene' \tag{46}$$

Variable Condition: All decision variables in the model are represented if one component will be chosen, so $b_{c_k,i,j}$ is a binary variable. Only one option can be chose from all available options for the specific component.

$$b_{c_k,i,j}\text{=0 or 1, (binary)} \tag{47}$$

$$\sum_{\mathrm{j}=1}^{n_k} b_{c_k,i,j} = 1\ , \forall\ i \in I\ , \forall\ c_k \in C_k \tag{48}$$

Component combination: As commonly known, some combinations of component options will not work because of the components' different physical properties. This constraint means that these two binary variables are not chosen '1' at the same time. S is the component notation for the components that cannot be assembled together.

$$b_{c_{k1},i,j1} + b_{c_{k2},i,j2} \leq 1, \forall\ i \in I, \forall\ (c_{k1}, j1, c_{k2}, j2) \in S \tag{49}$$

Weight of criteria: The weight of different criteria should be equal to 1, for all the equations when weight are used.

$$\mathrm{w}_1 + \mathrm{w}_2 + \mathrm{w}_3 = 1 \tag{50}$$

$$we_1 + we_2 = 1 \tag{51}$$

$$w_{cs} + w_{se} + w_{sa} + w_{da} + w_{re} = 1 \tag{52}$$

4.6 Objective Function

As discussed in the methodology, the objective of this optimization problem is to maximize sustainability of the product family. In order to model sustainability, the objective of this model will be modified to minimize Z, which means reducing cost of the total product family, reducing environmental impact, and increasing societal benefit. Sustainability is improved when Z is less. Equation (53) shows the final formulation of sustainability of the product family, the value for which is obtained using the Equations (54), (55), and (56). Equation (57) shows how the cost of the product family is computed. Equation (55) shows the environmental evaluation of the product family, and Equation (56) shows the societal evaluation of the product family. C, E, and S are cost, environmental, and societal metrics respectively, and have different units. They are normalized when using in Equation (53) as shown.

$$Z = \mathrm{w}_1 \cdot C/C' + \mathrm{w}_2 \cdot E - \mathrm{w}_3 \cdot S/S' \tag{53}$$

$$C = CR + Codd + CF + CP - RR \tag{54}$$

$$E = we_1 \cdot Ene/Ene' + we_2 \cdot COE/COE' \quad (55)$$

$$S = w_{cs} \cdot CS + w_{se} \cdot SE/SE' + w_{sa} \cdot SA + w_{da} \cdot DA + w_{re} \cdot RE \quad (56)$$

Where *C'*, *S'*, *Ene'*, *COE'* are data from an existing product used to normalize *C*, S, *Ene* and *COE*. w_1, w_2, w_3 are weight of cost, environmental and societal factors, and w_{cs}, w_{se}, w_{sa}, w_{da}, w_{re} are weight of societal factors. $CR, Codd, CF, CP, and\ RR$ are the cost of raw material, design and development, facilities, and processing, and the revenue from recycling respectively. Ene and COE are energy consumption and CO_2 emission of the product family. *CS*, *SE*, *SA*, *DA*, *RE* are Customer Satisfaction, Service, Safety, Disassemblability, and Recyclability.

4.7 Summary

Based on the discussion presented for the formulation of the mathematical model can be summarized as follows:

Objective:

Maximize Sustainability of product family (Minimize Z)

$$Minimize:\ Z = w_1 \cdot C/C' + w_2 \cdot E - w_3 \cdot S/S' \quad (57)$$

Where,

$$C = CR + Codd + CF + CP - RR \quad (58)$$

$$E = we_1 \cdot Ene/Ene' + we_2 \cdot COE/COE' \quad (59)$$

$$S = w_{cs} \cdot CS + w_{se} \cdot SE/SE' + w_{sa} \cdot SA + w_{da} \cdot DA + w_{re} \cdot RE \quad (60)$$

$$CR = \sum_{c_k=1}^{nc} CR_{c_k} \tag{61}$$

$$Codd = \sum_{c_k=1}^{nc} Codd_{c_k} \tag{62}$$

$$CF = \sum_{c_k=1}^{nc} CF_{c_k} \tag{63}$$

$$LC = \sum_{c_k=1}^{nc} LC_{c_k} \tag{64}$$

$$EC = Ene \cdot ECH \tag{65}$$

$$CP = EC + LC \tag{66}$$

$$COE = \sum_{c_k=1}^{nc} COE_{c_k} \tag{67}$$

$$Ene = \sum_{c_k=1}^{nc} Ene_{c_k} \tag{68}$$

$$CS = (\sum_{c_k=1}^{nc} CS_{c_k})/(nc \cdot 10 \cdot \sum_{i=1}^{np} N_i) \tag{69}$$

$$CN = \sum_{c_k=1}^{nc} CN_{c_k} \tag{70}$$

$$SE = \alpha - \beta \cdot CN \tag{71}$$

$$SA = (\sum_{c_k=1}^{nc} SA_{c_k})/(\sum_{i=1}^{np} N_i \cdot (\sum_{k=1}^{nc} n_{k,m}) \cdot 9) \tag{72}$$

$$DA = \mu - \nu \cdot CN \tag{73}$$

$$RE = (\sum_{c_k=1}^{nc} RE_{c_k}) / (nc \cdot \sum_{i=1}^{np} N_i) \tag{74}$$

$$RR = (\sum_{c_k=1}^{nc} RE_{c_k}) \tag{75}$$

Subject to:

$$\sum_{c_k=1}^{nc} (\sum_{j=1}^{n_k} (b_{c_k,i,j} \cdot FP_{c_k,j})) < FPM_{i+1}, \forall\, i \in I \tag{76}$$

$$\sum_{c_k=1}^{nc} (\sum_{j=1}^{n_k} (b_{c_k,i,j} \cdot FP_{c_k,j})) \geq FPM_i, \forall\, i \in I \tag{77}$$

$$COE \leq (1 - \alpha\%) \cdot COE' \tag{78}$$

$$Ene \leq (1 - \alpha\%) \cdot Ene' \tag{79}$$

$$b_{c_k,i,j}\text{=0 or 1, (binary)} \tag{80}$$

$$\sum_{\mathrm{j}=1}^{n_k} b_{c_k,i,j} = 1 \text{ , } \forall\, i \in I \text{ , } \forall\, c_k \in C_k \tag{81}$$

$$b_{c_{k1},i,j1} + b_{c_{k2},i,j2} \leq 1, \forall\, i \in I, \forall\, (c_{k1}, j1, c_{k2}, j2) \in S \tag{82}$$

$$\mathrm{w}_1 + \mathrm{w}_2 + \mathrm{w}_3 = 1 \tag{83}$$

$$we_1 + we_2 = 1 \tag{84}$$

$$w_{cs} + w_{se} + w_{sa} + w_{da} + w_{re} = 1 \tag{85}$$

A case study will be showed in the next section to formulate the model.

5. Case study

This chapter presents a case study using a family of bicycles to demonstrate the application of the proposed models and discussed in Chapters 4. The results will help managers to make decisions about optimal product platform configuration. The detailed framework of the proposed methodology is shown in Figure 13.

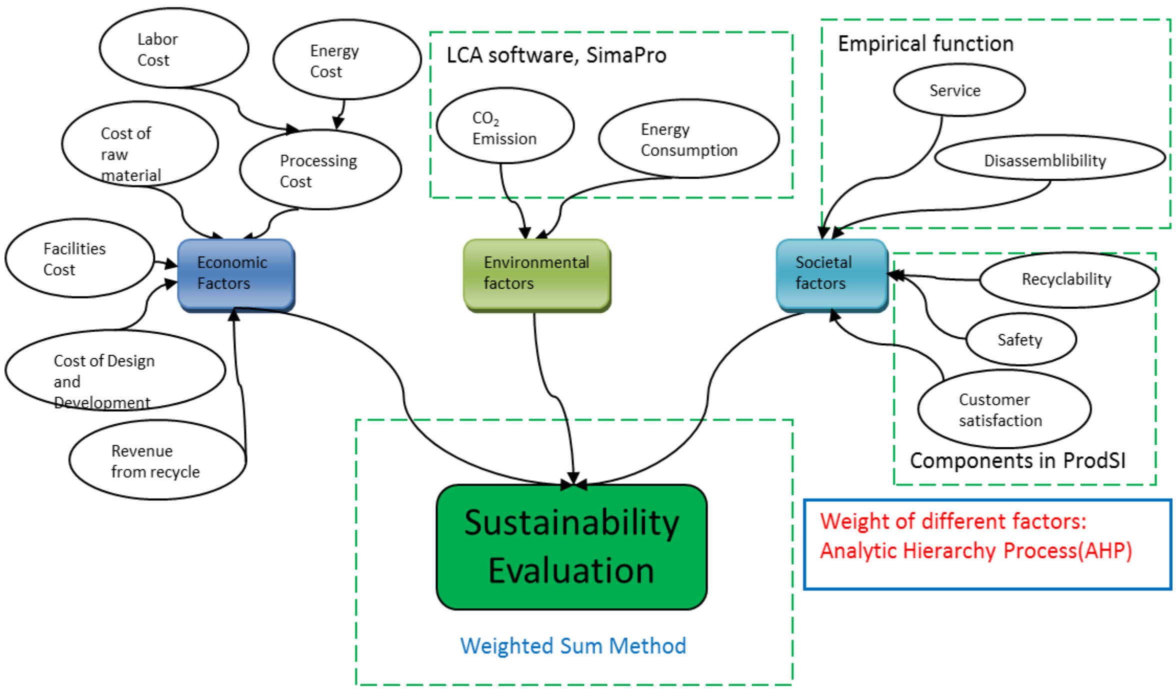

Figure 13: Framework for sustainable product family design

5.1 Bicycle Product Platform Configuration

Suppose that a bicycle company offers a variety of bicycle designs for customers that can be individualized to personal requirements. Each bicycle component that is customizable is referred to as a feature and several options are available for each of the features. A market survey is conducted to research what the customers really need with final results showing that different customers have different requirement for the frame, fork, handle bar, pedals, and wheel. These parts can be custom manufactured in-house after receiving the customer's order. In total, we assumed that there 16 frame options, 20 fork options, 20 handle bar options, 6 wheel options, and 5 pedal options that customer can choose from. These different options differ in term of type of material, design, shape, and dimensions (See Table 8). Examples of some selected components obtained from various sources on the internet is shown in Figure 15. These feature-options together offer 192,000 ($16 \times 20 \times 20 \times 6 \times 5$) different bicycle models (See Table 8). Detailed information about these components is in the Appendix B.

A customer can choose options from Table 8 to construct a bicycle. Some selected components are showed in Figure 14. Each customer can choose one frame, one fork, one handle bar, one wheel, and one pedal to construct a bicycle that fulfills their requirement.

However, fulfilling all the requirements of all the customers will make the cost very high. Customers can be divided into different groups according to similar requirements. The most important product performance features that customers value must be identified to satisfy the requirements of different groups of customers. The goal is to design a sustainable bicycle platform that reduces cost and simultaneously meets customer requirements. Due to the fact that there are not enough data available at hand, this case study will be based on some assumed data and scenarios, for example, customer satisfaction of all the customers, the real sales data of all the bicycles. The assumed data will be presented in the following sub-sections.

Table 8: Number of Feature-Options for Custom Manufactured Features

Feature	Number of Feature-options	Variations(materials, design, shape, and dimensions)
Frame	16	Aluminum, Titanium, Steel, Carbon Fiber, different design and shape
Fork	20	Aluminum, Titanium, Steel, Carbon Fiber, different design and shape
Handle bar	20	Aluminum, Titanium, Steel, Carbon Fiber, different design and shape
Wheel	6	Alloy, Carbon Fiber, Size, and shape
Pedals	5	Aluminum, Magnesium, Plastic, and different design

Figure 14: Selected components for the case study

5.2 Design Scenario

The weight is a major factor for customers to consider when choosing a bicycle. To fulfill the requirements of all customers, a market segmentation process can be conducted according to different weights. It is assumed that 4 market segments will be made and that the weight range of these segments will be the same. Four bicycle models will be chosen from 192,000 combinations to fulfill all customer requirements. The number of bicycles needed for each market segment can be obtained from the company's marketing department. However, we do not have a real data-base of bicycle marketing. So some data will be assumed here as sources to demonstrate the methodology. The weight ranges and number of products needed for each market segment are summarized in Table 9.

Table 9: Weight range and product demand

Market segment	Product	Weight range(kg)	Number of products needed
Light	1	2.53 – 4.51	58839
Regular 1	2	4.51 – 6.49	107085
Regular 2	3	6.49 - 8.47	23989
Heavy	4	8.47 - 10.45	2087

5.3 Data Preparation

In order to use the currently proposed model, environmental and social evaluation needs to be conducted for all of the components with data imported to the mathematical model. The following sub-sections will introduce the data and how the data is collected/generated.

5.3.1 Data Sources

Many datasets will be used in the development of this mathematical model. The following section introduces the sources of all these input datasets. This mathematical model incorporates the manufacturing processes of all available components which came from a working paper at the University of Kentucky (Badurdeen, 2012). The weight of each component and other information for all of the components was obtained from bicycle component websites. Examples include the following: http://weightweenies. starbike.com /listings.php, http://www.chainreactioncycles.com/us/en/wellgo-b109-plastic-pedals/rp-prod70423, http://www.amazon.com, www.ebay.com, https://www.google.com/.

The customer satisfaction index, recyclability, manufacturing time, development cost of all components, and safety coefficient for all of the machines was randomly generated due to a lack of actual industry data. The cost of raw materials for aluminum, iron, titanium, carbon fiber, plastic, and magnesium were obtained from an international raw material price website, http://www.metalprices.com/. More detailed information will be presented in the following sections.

5.3.2 Weight Calculation with AHP for All the Other Factors

Weight of different metrics can be obtained with AHP. There are lots of software that can be used to calculate weight based on AHP method. Among these softwares, *Super Decisions*, is the best software to save time to do the complex calculation. Therefore *Super Decisions* is employed here to calculate weight of different criteria based on AHP. One example using Super Decisions is shown in Figure 15.

First, the number of criteria will be decided. There are three criteria in this example, economy, environment, and society. Second, make pairwise comparison between these three criteria. The relative weight of these three criteria will obtained with *Super Decisions* after pairwise comparison is done (Figure 15).

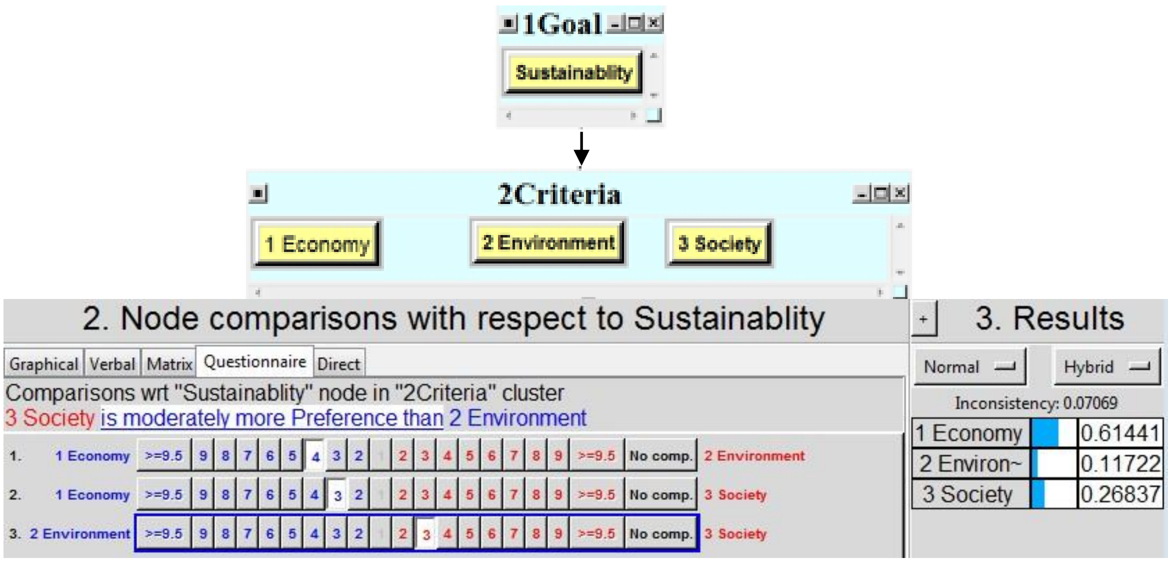

Figure 15: Weight of different factors through Super Decisions (Source: *Super Decisions*)

As we discussed in methodology (Chapters 3), AHP is very subjective and AHP results rely on the expertise of the person who conducted the comparison. In order to increase the accuracy of weight in the thesis, the comparison is conducted in multiple people and one questionnaire (Appendix C3) is sent to one research team in Institute of Sustainable Manufacturing in University of Kentucky. All the comparison of different criteria is averaged based on response of all the team member. Then the weight of different metrics is calculated from Super Decision and produce the averaged comparisons. The Weight of Economic, Environmental, and Societal Factors from *Super Decisions* is calculated and listed in Table 10.

Table 10: Weight of Economic, Environmental, and Societal factors

Factors	**Weight**
Economic	0.7
Environmental	0.2
Societal	0.1

The final result show that weight of economic factor is 0.7, the weight of environmental factor is 0.2, and the weight of societal factor is 0.1 based on the knowledge of the research team.

The weight of CO_2 Emission and Energy Consumption is shown in Table 11. The result show that the weight of CO_2 emission is 0.4 and the weight of Energy Consumption is 0.6 based on the response of the team.

Table 11: Weight of CO_2 Emission and Energy Consumption

Factors	**Weight**
CO_2 Emission	0.4
Energy Consumption	0.6

The weight of different societal factors is shown in Table 12. The result show that weight of Customer Satisfaction, Service, Safety, Disassemblibility, and Recyclability is 0.4, 0.15, 0.1, 0.17, 0.18, specifically.

Table 12: Weight of Societal Factors

Factors	Weight
Customer Satisfaction	0.4
Service	0.15
Safety	0.1
Disassemblibility	0.17
Recyclability	0.18

5.3.3 Environmental Evaluation of All the Components

In this case study, SimaPro will be utilized in the environmental evaluation of all components, 67 available components for this case study. The name of components in Table 13 is the order of the components in Appendix B. For example, Pedal 1 means that this pedal is the first pedal option in Appendix B5. The CO_2 emission and energy consumption of each component is also listed in Table 13 with data exported into the mathematical model, which is proposed in Chapter 4.

Table 13: CO_2 Emission and Energy Consumption Data

Components	CO_2 Emission (kg)	Energy Consumption(1000Mj)
Pedal 1	1.4	0.76
Pedal 2	1.02	0.48
Pedal 3	0.85	0.37
Pedal 4	0.82	0.36
Pedal 5	0.984	0.404
Wheel 1	0.78	3.05
Wheel 2	1.01	3.45
Wheel 3	0.64	2.76
Wheel 4	0.76	3
Wheel 5	1.29	5.55
Wheel 6	1.45	6

Handle bar 1	0.56	0.32
Handle bar 2	0.32	0.19
Handle bar 3	2.13	1.32
Handle bar 4	0.25	0.12
Handle bar 5	0.62	0.35
Handle bar 6	0.52	0.3
Handle bar 7	1.45	1.03
Handle bar 8	1.14	0.65
Handle bar 9	0.79	0.42
Handle bar 10	0.6	0.32
Handle bar 11	0.49	0.27
Handle bar 12	0.89	0.49
Handle bar 13	4.67	2.04
Handle bar 14	2.84	1.19
Handle bar 15	6.02	2.56
Handle bar 16	0.78	0.39
Handle bar 17	1.34	0.65
Handle bar 18	0.72	0.32
Handle bar 19	2.912	1.24
Handle bar 20	1.45	0.6
Fork 1	0.93	0.45
Fork 2	0.42	0.18
Fork 3	1.335	0.588
Fork 4	0.65	0.29
Fork 5	1.02	0.49
Fork 6	0.32	0.15
Fork 7	1.34	0.62
Fork 8	0.45	0.23
Fork 9	1.25	0.61
Fork 10	0.39	0.21
Fork 11	1.19	0.49
Fork 12	0.34	0.19
Fork 13	0.69	0.43
Fork 14	0.39	0.24
Fork 15	1.23	0.77
Fork 16	0.43	0.32
Fork 17	1.43	1.41
Fork 18	1.23	1.17
Fork 19	1.53	1.73
Fork 20	1.29	1.28
Frame 1	1.42	0.675
Frame 2	1.19	0.562
Frame 3	2.32	0.92

Frame 4	1.23	0.49
Frame 5	1.9	0.86
Frame 6	1.43	0.6
Frame 7	2.31	1.21
Frame 8	1.51	0.69
Frame 9	1.78	0.81
Frame 10	1.56	0.72
Frame 11	1.853	0.826
Frame 12	1.52	0.7
Frame 13	2.12	1.24
Frame 14	1.93	1.19
Frame 15	1.67	0.79
Frame 16	1.42	0.62

5.3.4 Societal Evaluation of All the Components

5.3.4.1 Customer Satisfaction

As we discuss in the methodology, the Customer Satisfaction Index (CSI) can be used to calculate customer satisfaction of each component based on each market segment. Customer satisfaction will be different in each market segment because the customer requirements are different in diverse markets. The Customer Satisfaction Index can be obtained with CSI criteria if we have real data. However, there is no real customer response data for this case study. So the data of Customer Satisfaction Index will be assumed here. The following tables list the assumed Customer Satisfaction Index of pedals, wheels, handle bar, fork, and frame based on different markets.

5.3.4.1.1 Customer Satisfaction of Pedals

Table 14: Customer Satisfaction of Pedals in Different Market

	Customer satisfaction of pedals			
Pedal	**Market 1**	**Market 2**	**Market 3**	**Market 4**
Pedal 1	5	6	7	10
Pedal 2	6	7	10	8
Pedal 3	9	10	6	6
Pedal 4	10	8	7	6
Pedal 5	8	8	8	8

5.3.4.1.2 Customer Satisfaction of Wheel

Table 15: Customer Satisfaction of Wheels in Different Market

	Customer satisfaction of wheel			
Wheel	**Market 1**	**Market 2**	**Market 3**	**Market 4**
Wheel 1	9	10	8	7
Wheel 2	6	7	10	8
Wheel 3	10	8	7	6
Wheel 4	9	8	8	7
Wheel 5	7	7	7	10
Wheel 6	7	7	6	9

5.3.4.1.3 Customer Satisfaction of Handle Bar

Table 16: Customer Satisfaction of Handle Bar in Different Market

	Customer satisfaction of Handle bar			
Handle bar	**Market 1**	**Market 2**	**Market 3**	**Market 4**
Handle bar 1	9	8	7	6
Handle bar 2	10	8	6	5
Handle bar 3	6	7	10	9
Handle bar 4	10	8	7	5
Handle bar 5	9	10	7	7
Handle bar 6	9	8	7	6
Handle bar 7	7	7	10	8
Handle bar 8	7	8	9	7
Handle bar 9	8	9	8	7
Handle bar 10	9	10	7	7

Handle bar 11	7	8	10	8
Handle bar 12	8	9	8	7
Handle bar 13	5	6	7	10
Handle bar 14	6	7	9	10
Handle bar 15	5	6	7	9
Handle bar 16	9	10	7	6
Handle bar 17	7	9	8	7
Handle bar 18	9	10	8	6
Handle bar 19	6	7	9	10
Handle bar 20	8	9	8	7

5.3.4.1.4 Customer Satisfaction of Fork

Table 17: Customer Satisfaction of Fork in Different Market

	Customer satisfaction of fork			
Fork	**Market 1**	**Market 2**	**Market 3**	**Market 4**
Fork 1	8	10	9	8
Fork 2	10	7	7	6
Fork 3	7	8	10	9
Fork 4	9	7	8	7
Fork 5	8	10	9	8
Fork 6	10	7	7	6
Fork 7	7	8	10	9
Fork 8	9	10	8	7
Fork 9	8	9	10	8
Fork 10	10	8	7	6
Fork 11	7	9	10	9
Fork 12	10	8	7	6
Fork 13	8	10	9	8
Fork 14	9	7	7	7
Fork 15	7	9	10	9
Fork 16	9	7	8	7
Fork 17	6	8	9	10
Fork 18	6	8	9	10
Fork 19	6	8	9	10
Fork 20	6	8	9	10

5.3.4.1.5 Customer Satisfaction of Frame

Table 18: Customer Satisfaction of Frame in Different Market

	Customer satisfaction of frame			
Frame	**Market 1**	**Market 2**	**Market 3**	**Market 4**
Frame 1	9	10	9	7
Frame 2	10	8	8	6
Frame 3	6	8	9	10
Frame 4	10	8	8	7
Frame 5	7	8	10	8
Frame 6	9	9	8	7
Frame 7	6	7	8	10
Frame 8	9	9	8	7
Frame 9	8	9	10	8
Frame 10	9	10	8	7
Frame 11	8	8	10	8
Frame 12	9	9	8	7
Frame 13	6	7	7	7
Frame 14	7	7	7	8
Frame 15	8	10	8	8
Frame 16	9	10	8	8

5.3.4.2 Safety

Safety metric evaluation is one part of societal metrics evaluation. Safety evaluation decide the safety of operator of machines. Each machine has its own safety coefficient. This information can be obtained from the factory record of accident rate. One example safety coefficient of all the machine that needed to make pedals is shown in Table 19 and other data is presented in Appendix C. 10 means that the machine is totally safe and have no accident, while 0 means that there are lots of accidents for the machine.

Table 19: Safety coefficient of all the machines needed for pedal

Data \ Machines Required	Mmachine Mg milling tool	Mmachine Al milling tool	Mmachine Plastic milling tool	Drilling Al tool	Drilling Mg tool	Drilling Plastic tool	Casting Mg pedals	Casting Al pedals	Al Extrusion	Knurling for Al	Injection moulding pedals	Pedal Assembly
Safety coefficient	7	7	8	7	6	8	7	7	7	7	7	8

5.3.4.3 Service

Real service data will be needed to obtain the accurate empirical function. In order to simplify our mathematical model proposed in Chapter 4, a linear service empirical function is assumed due to the fact that there is no data. The method to get the coefficient of the following formula is introduced in methodology. The empirical function of service is:

$$\mathrm{SE} = 0.96 - 0.022 * \mathrm{Var} \quad (76)$$

Var is the total number of components in the product family.

5.3.4.4 Disassemblibility

A linear disassemblibility empirical function is also assumed here to simplify the proposed model in Chapter 4. The method to get the following formula also is introduced in Methodology. The empirical function of disassemblibility is:

$$\mathrm{DA} = 1.06 - 0.032 * \mathrm{Var} \quad (77)$$

Var is the total number of components in the product family.

The empirical function of Service and Disassemblibility are a function of the total number of components in the product family. When the number of components in the product family increase, the service evaluation and disassemblibility evaluation decrease.

5.5 Model Formulation of the Case Study

After all data is collected/calculated, this case study is carried out following the mathematical model designed with the proposed methodology in Chapter 3. The detailed formulation of this case study's mathematical model is presented in Appendix A.

5.6 Results

This work utilized IBM ILOG Optimization Studio to solve the mathematical model. The final results of sustainable platform were identified. The comparison between sustainable platform based design and regular platform based design is also discussed in the following sub-sections. This model demonstrates what happens to sustainability when component sharing is changed. It also demonstrates what happens to cost and environmental and societal factors.

5.6.1 Sustainable Platform Results

After considering cost, environmental, and societal factors during the optimization process, the results of sustainable platform design are shown in Figure 16. The result show that Cast & Machined Mg pedals w/o knurling pedal, Size A3X, Y spoke Carbon Fiber wheel, and Al Fork Tapered straight legs with V crown w bolts w threaded steerer are chosen as platform by the mathematical model. The detailed information for these components are in presented in Table 20.

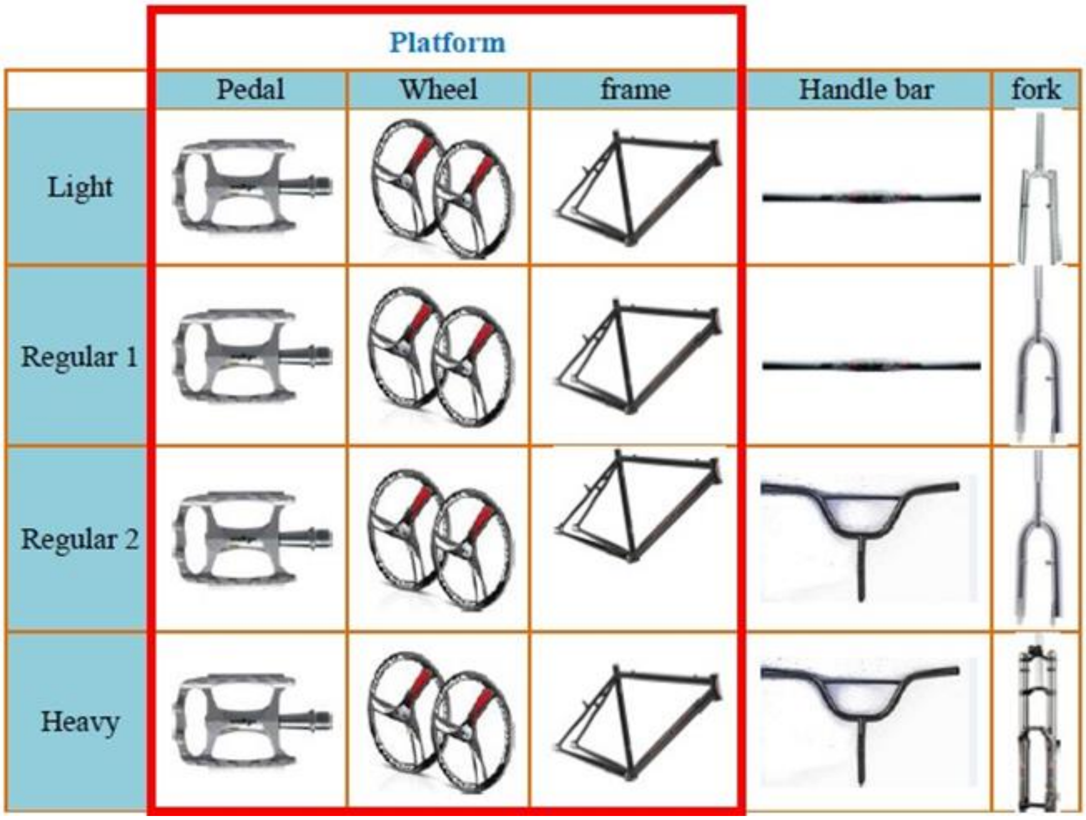

Figure 16: Platform chosen by the sustainable platform configuration design model

Table 20: Sustainable platform configuration design details

Market segment	Pedal	Wheel	Fork	Handle bar	Frame
Light	Cast & Machined Mg pedals w/o knurling	Size A3X, Y spoke Carbon Fiber wheel	Al Fork Tapered straight legs with V crown w bolts w threaded steerer	Al Single piece handle bar w/o cross bar	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube
Regular 1	Cast & Machined Mg pedals w/o knurling	Size A3X, Y spoke Carbon Fiber wheel	Steel Fork Non-tapered straight legs with curved crown	Al Single piece handle bar w/o cross bar	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube
Regular 2	Cast & Machined Mg pedals w/o knurling	Size A3X, Y spoke Carbon Fiber wheel	Steel Fork Non-tapered straight legs with curved crown	Steel Three piece handle bar w welded cross bar & tapered handles	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube
Heavy	Cast & Machined Mg pedals w/o knurling	Size A3X, Y spoke Carbon Fiber wheel	Al Fork Air sprung oil-damped	Steel Three piece handle bar w welded cross bar & tapered handles	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube

The sustainable platform is pedal, wheel, and frame, which means that the total product family will achieve the best sustainability when the pedals, wheels, and frames are shared between these different products.

5.6.2 Comparison of Sustainable Platform Based Design and Regular Platform Based Design

Regular platform based design only considers cost in the objective function while environmental and societal factors are not considered in objective function and constraints. In order to identify the regular platform, a new mathematical model is generated based on the mathematical model in Chapter 4 and only cost is considered in the final objective function of the model. The original objective function (Equation 78) is changed to cost (Equation 79) and the result of regular platform based design on this case study is shown in Figure 17. The detailed information of this chosen component is showed in Table 21.

$$\text{Minimize: } Z = \mathrm{w}_1 \cdot C/C' + \mathrm{w}_2 \cdot E - \mathrm{w}_3 \cdot S/S' \qquad (78)$$

$$\text{Minimize: } C \qquad (79)$$

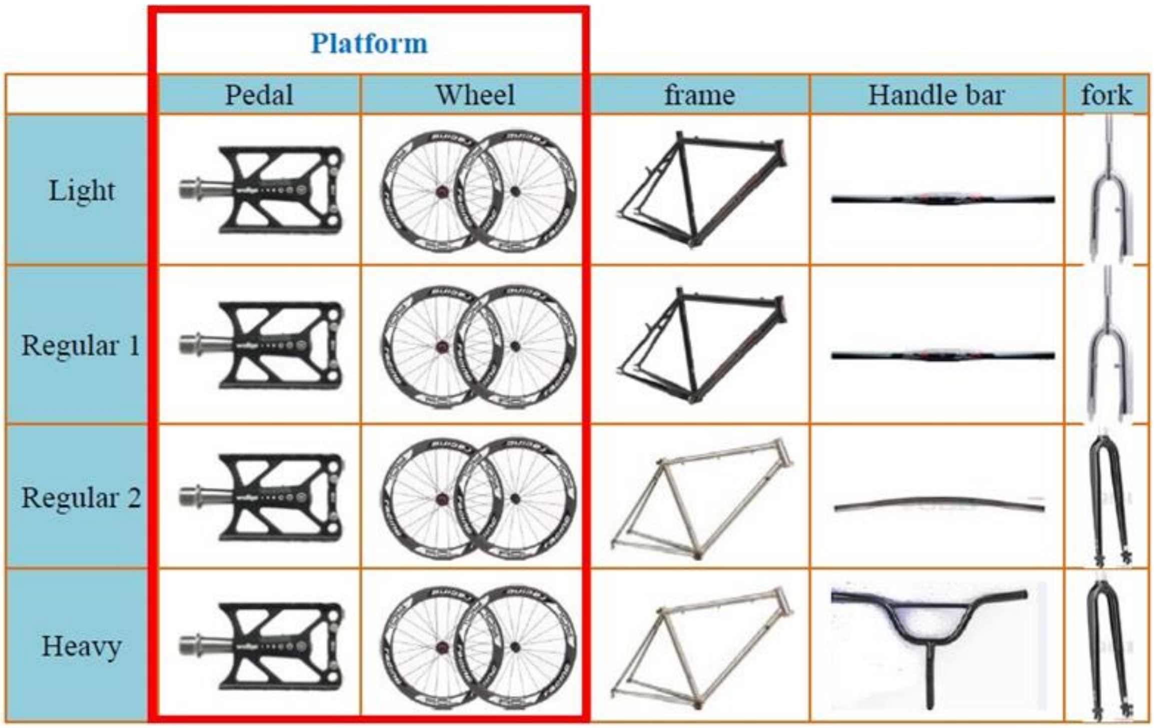

Figure 17: Platform chosen by regular platform based design

Table 21: Regular platform configuration design details

Market segment	Pedal	Wheel	Fork	Handle bar	Frame
Light	Extruded Al pedals	Size AX, Y spoke alloy wheel	Al Fork Non-tapered straight legs with curved crown	Al Single piece handle bar w/o cross bar	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube
Regular 1	Extruded Al pedals	Size AX, Y spoke alloy wheel	Steel Fork Non-tapered straight legs with curved crown	Al Single piece handle bar w/o cross bar	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube
Regular 2	Extruded Al pedals	Size AX, Y spoke alloy wheel	Steel Fork Non-tapered straight legs with flat inverted-T crown	Steel Single piece handle bar w/o cross bar	Standard Steel Frame with straight top tube, straight chain/seat stays, oversized head tube
Heavy	Extruded Al pedals	Size AX, Y spoke alloy wheel	Steel Fork Non-tapered straight legs with flat inverted-T crown	Steel Three piece handle bar w welded cross bar & tapered handles	Standard Steel Frame with straight top tube, straight chain/seat stays, oversized head tube

Comparison of the sustainable platform based design and the regular platform design is shown in Table 22. For sustainable platform based design, the cost will increase 42.3%, environmental impact will decrease 52.5%, and the societal factor remains nearly the same as compared to regular platform based design. Cost will have to be sacrificed in order to reduce environmental impact.

There are two reasons why the societal factor is nearly the same across designs. First, the weight of societal factors in final objective function of sustainable platform-based product family design is 0.1, which is small compared to cost and environmental factors in this case study. To achieve a higher sustainability, societal factors are the least factors that will affect sustainability. As a result, societal factors do not need to change significantly. Second, the final objective function of regular platform based design is cost. In order to minimize cost, more components need to be shared. Sharing more components will improve disassemblibility and service. As a result, some society factors will increase in regular platform based design. Cost will be minimized in regular platform design, which, in turn, will maximize some societal factors. Cost and environmental factors will be minimized and societal factors will be maximized in sustainable platform based design. In both designs, all societal factors will be maximized and societal factors will not be changed significantly.

Table 22: Comparison of Sustainable Platform Based Design and Regular Platform Design

Sustainability factors	Cost	Environment	Society
Regular platform based design	0.2702	0.9750	0.7601
Sustainable platform based design	0.3844	0.4627	0.7544
Change	+42.3%	-52.5%	-0.75%

5.6.3 Commonality and Sustainability

Component sharing is major feature of platform based design. In order to examine the relationship between components sharing and sustainability, more constraints must be added to the model to control the number of components shared in the product family. The sustainability rating can then be obtained when component sharing is varies from 0 to 5. Results are shown in Table 23 and Figure 18. The Z value will decrease as more components are shared, which means that when more components are shared, sustainability improves (lower score). The components selected for each scenario are shown next (Figure 18) to each data point. Components are gradually added as the number of platform size is increased.

When more components are shared, fewer components have to be designed with more equipment sharing which reduces cost, improves service, and increases disassemblibility to yield better societal performance. When four components are shared, the model becomes infeasible because the combination of components cannot be found to fulfill the weight requirement for different market segments.

Table 23: Component sharing and Z

Component sharing	0	1	2	3	4
Sustainability (Z)	0.32662	0.32663	0.3260	0.3256	Infeasible

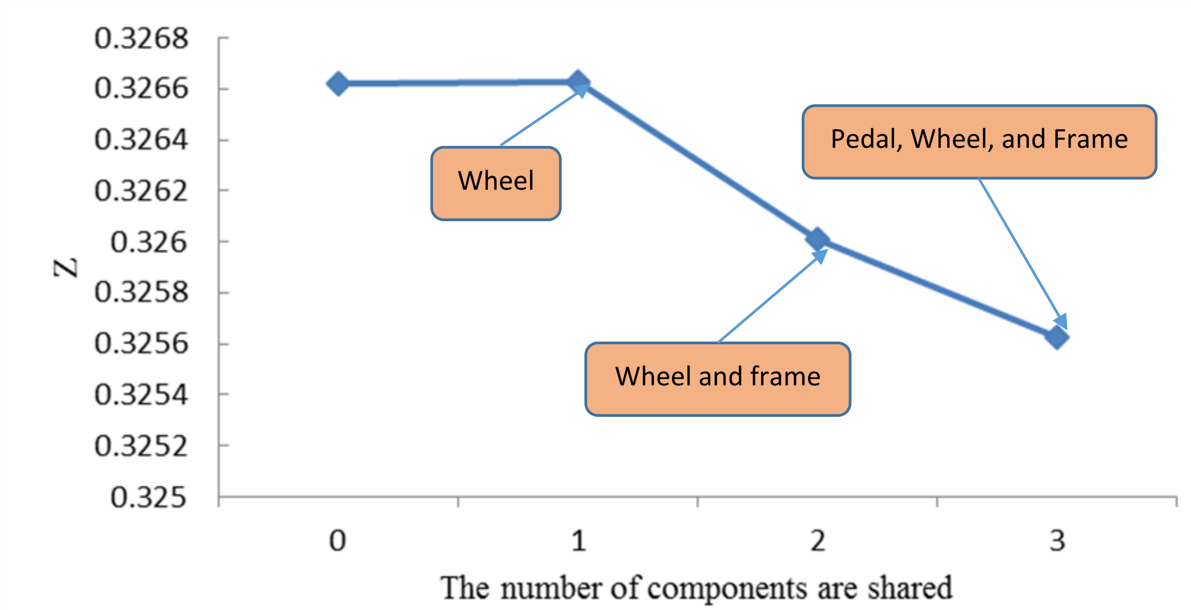

Figure 18: Component sharing and sustainability (note: sustainability is high when Z is low)

Sustainability is combination of environmental, economical, and social factors with different weight. When component sharing is changed, it is necessary to separately examine what happened to environmental, economic, and societal impact.

5.6.4 The Relationship between Commonality and Cost

In order to understand the platform better, the relationship between component commonality and cost also is investigated. The final results show that the cost of the product family is decreased when more components are shared (Figure 19). The cost includes labor costs, energy costs, raw material costs, facility costs, design and development, and recycle revenue. As discussed in methodology, labor costs will decrease when more components are shared due to the learning curve in the production process. The facility cost also will decrease when more components are shared.

Less machines will be needed if more components are shared, and, as a result, the factory will not need to buy so many machines with facility cost being saved. Design and development costs also decrease as more components are shared. With less components needed as more components are shared, less components need to be designed. Correspondingly, fewer engineers are needed and less design and development costs are incurred.

In summary, many factors in the cost of the product family are decreased when more components are shared. As a result, the total cost is decreased as more components are shared.

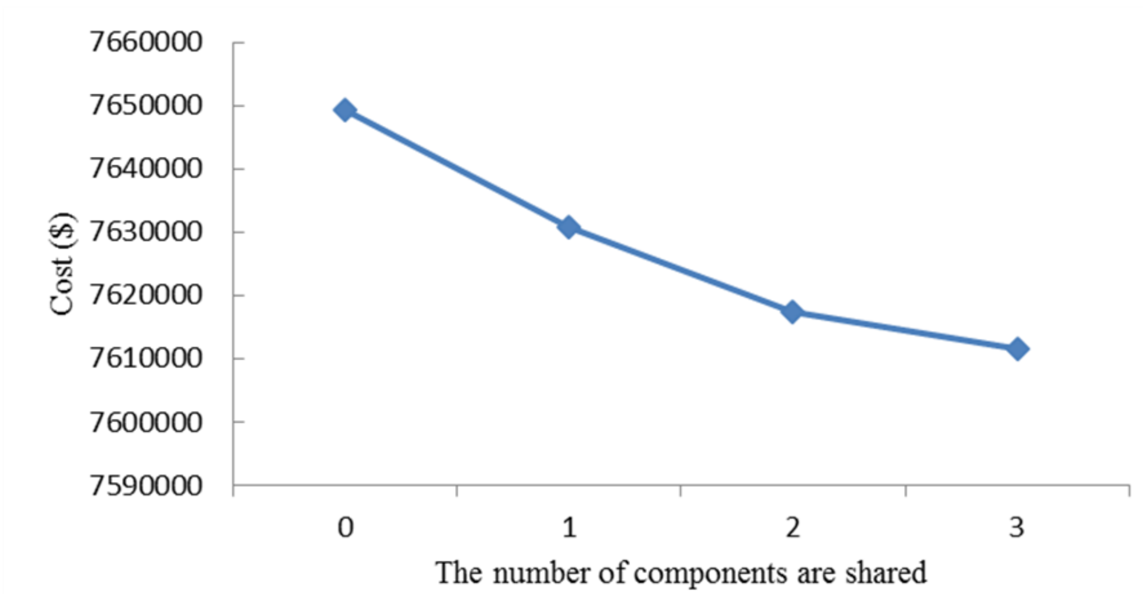

Figure 19: The relationship between cost and components sharing

5.6.5 Commonality and Environmental

Environmental impact determines if the design fulfills requirements of environmental regulations. CO_2 emission and energy consumption is one of the primary causes of global warming, a major concern of this century. In order to understand the relationship between components sharing and environmental impact, a specific optimization is achieved by adjusting the numbers for component sharing in the optimization. The relationship is presented in Figure 20.

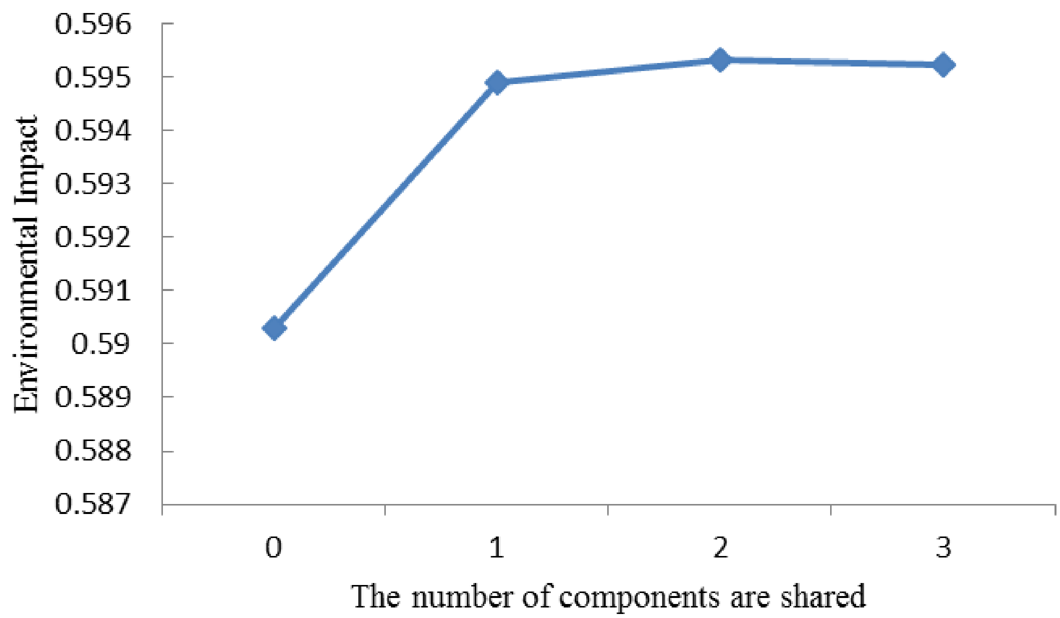

Figure 20: The relationship between environment and components sharing

Environmental impact will increase as more components are shared. The reason behind this occurrence is that environmental impact was not considered when more components are shared. Environmental assessment of the product family includes CO_2 emission and energy consumption evaluation obtained from SimaPro. The relationship between components sharing and CO_2 emission and energy consumption is unknown at this point, and, therefore, is not considered in the model. The final objective function of the optimization model is sustainability, a balance of cost, environmental factors, and societal factors. The weight of environmental impact is 0.2, very low when compared with cost and societal factors. As a result, the environmental factor is scarified in order to obtain better sustainability.

5.6.6 Commonality and Society

The relationship between societal factors is also studied here. The final result is shown in Figure 21.

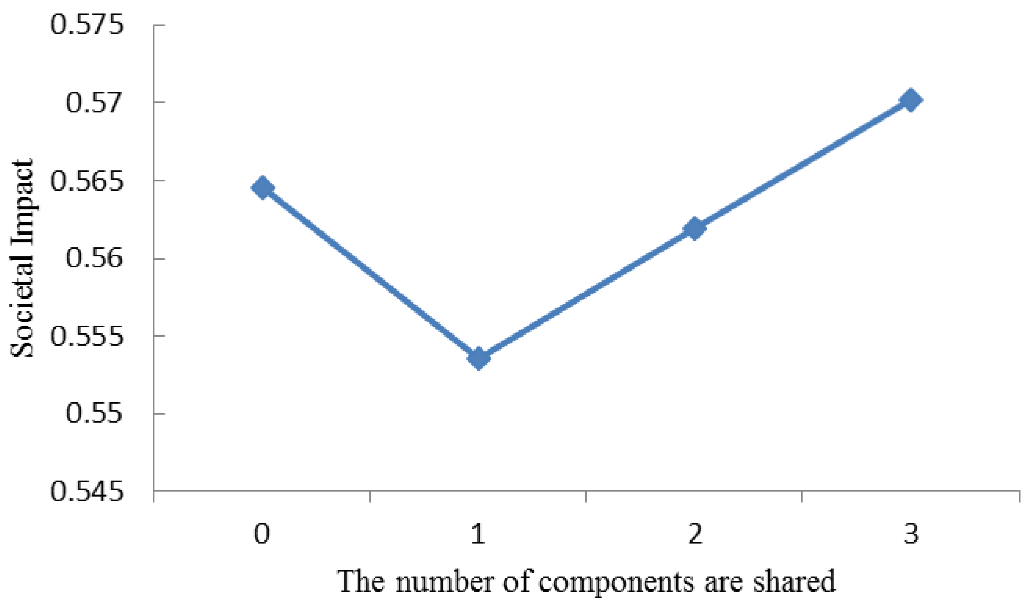

Figure 21: The relationship between societal impact and components sharing

As Figure 21 shows, societal impact will decrease first and then increase as more components are shared. There are two potential reasons for this. The societal factors include recyclability, service, disassemblibility, safety, and customer satisfaction. As discussed in the methodology section, service and disassemblibility will be improved when more components are shared, as sharing more components means that the worker will be more familiar with all of the products.

Factory safety of factory will also be improved as more components are shared because less machines will be needed and, as a result, accidents will be less likely to occur.

However, the relationship between recyclability and customer satisfaction and components sharing is currently unknown. It is possible that recyclability and customer satisfaction will not increase when component sharing increase from 0 to 1, while service, disassemblibility, safety do not increase a lot. The weight of recyclability and customer satisfaction in total societal impact is 0.17 and 0.4, respectively. As a result, recyclability and customer satisfaction are the major factors affecting the final societal evaluation and final societal performance do not increase a lot.

The weight of societal impact is 0.1. So societal factors will be sacrificed in order to achieve better sustainability compared with cost and environmental impact. As a result, societal impact decrease when component sharing increase from 0 to 1.

Service, disassembibilty, and safety will greatly increase as more components are shared and dominate the societal evaluation. As a result, societal impact increase a lot and societal impact will increase when component sharing is larger than 1.

6. Conclusions

Many companies consider sustainability when they design products to take into account their responsibility for protecting the environment. A large amount of research has been conducted to meet this requirement. Yet, sustainable product design has only considered single product design and one product design certainly cannot meet the requirements of all customers. To simultaneously meet the requirements of the majority of customers and to reduce cost, product family design is an excellent method. However, there have been very few research studies conducted to design a product family with consideration of total life-cycle sustainability.

This work provides a mathematical tool to help a company design a product family or redesign their product family to identify the components that can be shared and the platform to achieve the best total life-cycle sustainability. A mixed integer linear mathematical model is built to formulate the optimization problem and identify a sustainable platform to address total life-cycle sustainability.

Research was initiated by choosing metrics that could evaluate activities across the total life-cycle (from pre-manufacturing to post use) and from all aspects of the TBL. Specifically, economic, environmental, and social factors in pre−manufacturing, manufacturing, use, and post use stages were considered in the model. Several methods have been proposed to solve the problem. First, it is very difficult to evaluate environmental impact with no related data. This work utilized LCA software, SimaPro, to obtain the CO_2 emissions and energy consumption of all the manufacturing processes for all available components. Second, manufacturing cost will be reduced if more components are shared, which is a key characteristic of product family design. Learning curve was utilized to examine manufacturing costs when components are shared. Third, CSI can be used to evaluate customer satisfaction for components of individual products. This work modified the CSI and used it to evaluate customer satisfaction for components based on different markets. Fourth, in order to consider what happens to some societal factors when more components are shared, specifically disassemblability and service, an empirical function is introduced in the model. Sustainability is then formulated as a multi-objective optimization problem to increase economic impact, reduce environmental impact, and increase societal impact. Economic, environmental, and societal factors have different units, so these factors cannot be directly added together. In response, normalization is used with all the factors that have different units. Finally, this work used the AHP method to obtain all weights of different factors and proposed to use the weight sum method to solve the multi-objective optimization problem. The optimal product family platform configuration was determined by ILOG OPL optimization software.

A case study was used to demonstrate the effectiveness of the proposed model. The sustainable product platform was identified by the model and was compared with the regular platform. Results of interest include the following:

- Cost will increase in order to get high sustainability
- Sharing more components will improve sustainability

7. Future Work

This research is only in its initial stages and the model is not perfect. Much more work is needed to yield improvement in the future. The potential future works are listed as follows.

1. More metrics should be considered for a comprehensive sustainability evaluation. This work only considered cost as the economic factor and more economic factors need to be studied to represent the true economic impact of the product family. SimaPro could import more environmental related data from the manufacturing processes of all components. This data can then be used in the mathematical model. Because of the limited scope of this research, only CO_2 emissions and energy consumption were considered to evaluate environmental impact.

2. Better market segmentation strategies need to be initiated to understand what customers genuinely want from products. The weight of every bicycle was identified as the primary customer requirement for the market segment in this work. Real sales data can be obtained to analyze the actual preferences of different customers.

3. Product family design methodology could be improved. There is much research in product family design and many methodologies and tools have been developed, for example, two stages approach, multi-stage approach. New research can be done with implementation of all of these methodologies and focus on sustainability. MILP is used to solve this mathematical model in the thesis, and new optimization algorithm can be used to solve the problem.

4. The number of products needed in each market segment was an assumption in this work, but using a forecasted demand function to obtain the number of needed products could be a promising approach for future research.

5. An empirical function of service factors and disassemblability is assumed in this paper. Different industries and companies will have different service and disassemblability coefficients. Real data and corresponding suitable statistical methods will be very helpful in determining a more accurate empirical function. More accurate service and disassemblability evaluation can then be conducted.

6. Weighted sum methods were utilized to solve the multi-objective optimization problem and AHP method was used to obtain the weight of different factors. Other multi-objective optimization methods and the weights of criteria (e.g. Borda Count) could be employed.

Appendix A Detail Formulation of the Case Study

Objective function

min: $\quad Sustainability = w1 * C/C' + w2 * E - w3 * S/S'$

Where $C = CR + Codd + CF + CP - RR$

$$CR = CR_{pedal} + CR_{Wheel} + CR_{handle\ bar} + CR_{fork} + CR_{frame}$$

$$CR_{pedal} = \sum_{i=1}^{4}(N_i * (\sum_{j=1}^{5} b_{pedal,i,j} * W_{pedal,j} * C_{pedal,j}))$$

$$CR_{Wheel} = \sum_{i=1}^{4}(N_i * (\sum_{j=1}^{6} b_{Wheel,i,j} * W_{Wheel,j} * C_{Wheel,j}))$$

$$CR_{handle\ bar} = \sum_{i=1}^{4}(N_i * (\sum_{j=1}^{20} b_{handle\ bar,i,j} * W_{handle\ bar,j} * C_{handle\ bar,j}))$$

$$CR_{fork} = \sum_{i=1}^{4}(N_i * (\sum_{j=1}^{20} b_{fork,i,j} * W_{fork,j} * C_{fork,j}))$$

$CR_{frame} = \sum_{i=1}^{4}(N_i * (\sum_{j=1}^{16} b_{frame,i,j} * W_{frame,j} * C_{frame,j}))$ $Codd = Codd_{pedal} + Codd_{Wheel} + Codd_{handle\ bar} + Codd_{fork} + Codd_{frame}$

$$Codd_{pedal} = \sum_{j=1}^{5}(b_{pedal,1,j} \cup .. b_{pedal,3,j}) * Codd_{pedal,j}$$

$$Codd_{wheel} = \sum_{j=1}^{6}(b_{wheel,1,j} \cup .. b_{wheel,3,j}) * Codd_{wheel,j}$$

$$Codd_{handle\ bar} = \sum_{j=1}^{20}(b_{handle\ bar,1,j} \cup .. b_{handle\ bar,3,j}) * Codd_{handle\ bar,j}$$

$$Codd_{fork} = \sum_{j=1}^{20}(b_{fork,1,j} \cup .. b_{fork,3,j}) * Codd_{fork,j}$$

$$Codd_{frame} = \sum_{j=1}^{16}(b_{frame,1,j} \cup .. b_{frame,3,j}) * Codd_{frame,j}$$

$$CF = CF_{pedal} + CF_{Wheel} + CF_{handle\ bar} + CF_{fork} + CF_{frame}$$

$$CF_{pedal} = \sum_{k=1}^{12} CE_{pedal,k} * (bm_{pedal,1,k} \cup .. bm_{pedal,3,k})$$

$$CF_{wheel} = \sum_{k=1}^{13} CE_{wheel,k} * (bm_{wheel,1,k} \cup .. bm_{wheel,3,k})$$

$$CF_{fork} = \sum_{k=1}^{28} CE_{fork,k} * (bm_{fork,1,k} \cup .. bm_{fork,3,k})$$

$$CF_{handle\ bar} = \sum_{k=1}^{20} CE_{handle\ bar,k} * (bm_{handle\ bar,1,k} \cup .. bm_{handle\ bar,3,k})$$

$$CF_{frame} = \sum_{k=1}^{27} CE_{frame,k} * (bm_{frame,1,k} \cup .. bm_{frame,3,k})$$

$$CP = EC + LC$$

$$EC = Ene * ECH$$

$$LC = LC_{pedal} + LC_{Wheel} + LC_{handle\ bar} + LC_{fork} + LC_{frame}$$

$$LC_{pedal} = \sum_{j=1}^{5} \left(\left(B_{pedal,j} - A_{pedal,j} * \left(\sum_{i=1}^{3} b_{pedal,i,j} * N_i \right) \right) * \left(\sum_{i=1}^{3} b_{pedal,i,j} * N_i \right) * LCH \right)$$

$$LC_{wheel} = \sum_{j=1}^{6} \left(\left(B_{wheel,j} - A_{wheel,j} * \left(\sum_{i=1}^{3} b_{wheel,i,j} * N_i \right) \right) * \left(\sum_{i=1}^{3} b_{wheel,i,j} * N_i \right) * LCH \right)$$

$$LC_{handle\ bar} = \sum_{j=1}^{20} \left(\left(B_{handle\ bar,j} - A_{handle\ bar,j} * \left(\sum_{i=1}^{3} b_{handle\ bar,i,j} * N_i \right) \right) * \left(\sum_{i=1}^{3} b_{handle\ bar,i,j} * N_i \right) * LCH \right)$$

$$LC_{fork} = \sum_{j=1}^{20} \left(\left(B_{fork,j} - A_{fork,j} * \left(\sum_{i=1}^{3} b_{fork,i,j} * N_i \right) \right) * \left(\sum_{i=1}^{3} b_{fork,i,j} * N_i \right) * LCH \right)$$

$$LC_{frame} = \sum_{j=1}^{16}\left(\left(B_{frame,j} - A_{frame,j} * \left(\sum_{i=1}^{3} b_{frame,i,j} * N_i\right)\right) * \left(\sum_{i=1}^{3} b_{frame,i,j} * N_i\right) * LCH\right)$$

$$E = we1 * Ene/Ene' + we2 * COE/COE'$$

$$COE = COE_{pedal} + COE_{Wheel} + COE_{handle\ bar} + COE_{fork} + COE_{frame}$$

$$COE_{pedal} = \sum_{i=1}^{3}\sum_{j=1}^{5} b_{pedal,i,j} * W_{pedal,j} * COEr_{pedal,j} * N_i$$

$$COE_{wheel} = \sum_{i=1}^{3}\sum_{j=1}^{6} b_{wheel,i,j} * W_{wheel,j} * COEr_{wheel,j} * N_i$$

$$COE_{handle\ bar} = \sum_{i=1}^{3}\sum_{j=1}^{20} b_{handle\ bar,i,j} * W_{handle\ bar,j} * COEr_{handle\ bar,j} * N_i$$

$$COE_{fork} = \sum_{i=1}^{3}\sum_{j=1}^{20} b_{fork,i,j} * W_{fork,j} * COEr_{fork,j} * N_i$$

$$COE_{frame} = \sum_{i=1}^{3}\sum_{j=1}^{16} b_{frame,i,j} * W_{frame,j} * COEr_{frame,j} * N_i$$

$$Ene = Ene_{pedal} + Ene_{Wheel} + Ene_{handle\ bar} + Ene_{fork} + Ene_{frame}$$

$$Ene_{pedal} = \sum_{i=1}^{3}\sum_{j=1}^{5} b_{pedal,i,j} * W_{pedal,j} * Ener_{pedal,j} * N_i$$

$$Ene_{wheel} = \sum_{i=1}^{3}\sum_{j=1}^{6} b_{wheel,i,j} * W_{wheel,j} * Ener_{wheel,j} * N_i$$

$$Ene_{handle\ bar} = \sum_{i=1}^{3}\sum_{j=1}^{20} b_{handle\ bar,i,j} * W_{handle\ bar,j} * Ener_{handle\ bar,j} * N_i$$

$$Ene_{fork} = \sum_{i=1}^{3}\sum_{j=1}^{20} b_{fork,i,j} * W_{fork,j} * Ener_{fork,j} * N_i$$

$$Ene_{frame} = \sum_{i=1}^{3}\sum_{j=1}^{16} b_{frame,i,j} * W_{frame,j} * Ener_{frame,j} * N_i$$

$$S = \mathrm{wcs} * \mathrm{CS} + \mathrm{wse} * \mathrm{SE} + \mathrm{wsa} * \mathrm{SA} + \mathrm{wda} * \mathrm{DA} + \mathrm{wre} * \mathrm{RE}$$

$$CS = (CS_{pedal} + CS_{Wheel} + CS_{handle\ bar} + CS_{fork} + CS_{frame})/(nc \times 10 * \sum_{i=1}^{3} N_i)$$

$$CS_{pedal} = \sum_{i=1}^{3} \sum_{j=1}^{5} b_{pedal,i,j} * CS_{pedal,i,j} * N_i$$

$$CS_{wheel} = \sum_{i=1}^{3} \sum_{j=1}^{6} b_{wheel,i,j} * CS_{wheel,i,j} * N_i$$

$$CS_{handle\ bar} = \sum_{i=1}^{3} \sum_{j=1}^{20} b_{handle\ bar,i,j} * CS_{handle\ bar,i,j} * N_i$$

$$CS_{fork} = \sum_{i=1}^{3} \sum_{j=1}^{20} b_{fork,i,j} * CS_{fork,i,j} * N_i$$

$$CS_{frame} = \sum_{i=1}^{3} \sum_{j=1}^{20} b_{frame,i,j} * CS_{frame,i,j} * N_i$$

$$SE = \alpha - \beta * CN$$

$$CN = CN_{pedal} + CN_{Wheel} + CN_{handle\ bar} + CN_{fork} + CN_{frame}$$

$$CN_{pedal} = \sum_{j=1}^{5} (b_{pedal,1,j} \cup .. b_{pedal,3,j})$$

$$CN_{wheel} = \sum_{j=1}^{6} (b_{wheel,1,j} \cup .. b_{wheel,3,j})$$

$$CN_{handle\ bar} = \sum_{j=1}^{20} (b_{handle\ bar,1,j} \cup .. b_{handle\ bar,3,j})$$

$$CN_{fork} = \sum_{j=1}^{20} (b_{fork,1,j} \cup .. b_{fork,3,j})$$

$$CN_{frame} = \sum_{j=1}^{16} (b_{frame,1,j} \cup .. b_{frame,3,j})$$

$$SA = (SA_{pedal} + SA_{Wheel} + SA_{handle\ bar} + SA_{fork} + SA_{frame}) / (\sum_{i=1}^{3} N_i \times (\sum_{k=1}^{5} n_m^k) \times 9)$$

$$SA_{pedal} = \sum_{i=1}^{3} N_i * (\sum_{j=1}^{5} (b_{pedal,i,j} * \sum_{k=1}^{12} (bb_{pedal,j,k} * SA_{pedal,k})))$$

$$SA_{wheel} = \sum_{i=1}^{3} N_i * (\sum_{j=1}^{5} (b_{wheel,i,j} * \sum_{k=1}^{13} (bb_{wheel,j,k} * SA_{wheel,k})))$$

$$SA_{handle\ bar} = \sum_{i=1}^{3} N_i * (\sum_{j=1}^{5} (b_{handle\ bar,i,j} * \sum_{k=1}^{28} (bb_{handle\ bar,j,k} * SA_{handle\ bar,k})))$$

$$SA_{fork} = \sum_{i=1}^{3} N_i * (\sum_{j=1}^{5}(b_{fork,i,j} * \sum_{k=1}^{20}(bb_{fork,j,k} * SA_{fork,k})))$$

$$SA_{frame} = \sum_{i=1}^{3} N_i * (\sum_{j=1}^{5}(b_{frame,i,j} * \sum_{k=1}^{27}(bb_{frame,j,k} * SA_{frame,k})))$$

$$DA = \mu - \nu * CN$$

$$RE = (RE_{pedal} + RE_{Wheel} + RE_{handle\ bar} + RE_{fork} + RE_{frame})/\ (nc * \sum_{i=1}^{3} N_i)$$

$$RE_{pedal} = \sum_{i=1}^{3} \sum_{j=1}^{5}(b_{pedal,i,j} * RE_{pedal,j} * N_i)$$

$$RE_{wheel} = \sum_{i=1}^{3} \sum_{j=1}^{6}(b_{wheel,i,j} * RE_{wheel,j} * N_i)$$

$$RE_{handle\ bar} = \sum_{i=1}^{3} \sum_{j=1}^{20}(b_{handle\ bar,i,j} * RE_{handle\ bar,j} * N_i)$$

$$RE_{fork} = \sum_{i=1}^{3} \sum_{j=1}^{20}(b_{fork,i,j} * RE_{fork,j} * N_i)$$

$$RE_{frame} = \sum_{i=1}^{3} \sum_{j=1}^{20}(b_{frame,i,j} * RE_{frame,j} * N_i)$$

$$RR = RR_{pedal} + RR_{Wheel} + RR_{handle\ bar} + RR_{fork} + RR_{frame}$$

$$RR_{pedal} = \sum_{i=1}^{3} \sum_{j=1}^{5}(b_{pedal,i,j} * RE_{pedal,j} * W_{pedal,i,j} * C_{pedal,i,j1} * N_i)$$

$$RR_{wheel} = \sum_{i=1}^{3} \sum_{j=1}^{6}(b_{wheel,i,j} * RE_{wheel,j} * W_{wheel,i,j} * C_{wheel,i,j1} * N_i)$$

$$RR_{handle\ bar} = \sum_{i=1}^{3} \sum_{j=1}^{20}(b_{handle\ bar,i,j} * RE_{handle\ bar,j} * W_{handle\ bar,i,j} * C_{handle\ bar,i,j1} * N_i)$$

$$RR_{fork} = \sum_{i=1}^{3} \sum_{j=1}^{20}(b_{fork,i,j} * RE_{fork,j} * W_{fork,i,j} * C_{fork,i,j1} * N_i)$$

$$RR_{frame} = \sum_{i=1}^{3} \sum_{j=1}^{16}(b_{frame,i,j} * RE_{frame,j} * W_{frame,i,j} * C_{frame,i,j1} * N_i)$$

Appendix B The Manufacturing Process of All the Components

Appendix B1 Frame Feature-Options Available with MyBike

	Frame Options \ Machines Required	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Mmachine Al milling tool	Mmachine Ti milling tool	Mmachine Steel milling tool	Drilling Al tool	Thread cutting Al	Thread cutting Ti	Thread cutting Steel	Welding Al	Welding Ti	Welding Steel	Bending Frame parts	Frame holding fixture	Crosstrac frame fixture	Al Stamping/Forming	Surface finishing	Painting	Frame Assembly	Carbon Fiber moulding/Frame	Pressurized heating Chamber for CF moul	Assembly & gluing CF parts	Polishing & painting CF parts
1	Al Frame with curved top tube, curved chain/seat stays, oversized head tube	x			x			x				x			x			x	x			x	x	x				
2	Ti Frame with curved top tube, curved chain/seat stays, oversized head tube		x			x			x				x			x		x	x			x		x				
3	Steel Frame with curved top tube, curved chain/seat stays, oversized head tube			x			x			x				x			x	x	x			x	x	x				
4	Carbon Fiber Frame with curved top tube, curved chain/seat stays, oversized head tube																								x	x	x	x
5	Standard Al Frame with straight top tube, straight chain/seat stays, oversized head tube	x						x				x			x				x			x	x	x				
6	Standard Ti Frame with straight top tube, straight chain/seat stays, oversized head tube		x						x				x			x			x			x		x				
7	Standard Steel Frame with straight top tube, straight chain/seat stays, oversized head tube			x						x				x			x		x			x	x	x				
8	Standard Carbon Fiber Frame with straight top tube, straight chain/seat stays, oversized head tube																								x	x	x	x
9	Standard Al Frame with straight top tube, straight chain/seat stays, standard head tube	x						x				x			x				x			x	x	x				
10	Standard Ti Frame with straight top tube, straight chain/seat stays, standard head tube		x						x				x			x			x			x		x				
11	Standard Steel Frame with straight top tube, straight chain/seat stays, standard head tube			x						x				x			x		x			x	x	x				
12	Standard Carbon Fiber Frame with straight top tube, straight chain/seat stays, standard head tube																								x	x	x	x
13	Al Crosstrac Suspension Frame	x						x			x									x	x	x	x	x				
14	Carbon Fiber Crosstrac Suspension Frame																					x	x	x	x	x	x	x
15	Al Softride Power V Frame	x						x			x				x						x	x		x				
16	Carbon Fiber Softride Power V Frame																								x	x	x	x

Appendix B2 Fork Feature-Options Available With MyBike

	Fork Options \ Machines Required	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Mmachine Al milling tool	Mmachine Ti milling tool	Mmachine Steel milling tool	Drilling Al tool	Drilling Mg tool	Drilling Ti tool	Drilling Steel tool	Thread cutting Al	Thread cutting Ti	Thread cutting Steel	Welding Al	Welding Ti	Welding Steel	Bending Fork/Frame parts	Fork holding fixture	Surface finishing	Painting	Fork Assembly	Carbon Fiber moulding/Fork	Pressurized heating Chamber for CF moulds	Assembly & gluing CF parts	Polishing & painting CF parts
1	Al Fork Non-tapered straight legs with curved crown	x																x			x	x	x	x	x				
2	Ti Fork Non-tapered straight legs with curved crown		x																x		x	x	x		x				
3	Steel Fork Non-tapered straight legs with curved crown			x																x	x	x	x	x	x				
4	Carbon Fiber Fork Non-tapered straight legs with curved crown																									x	x	x	x
5	Al Fork Non-tapered straight legs with flat inverted-T crown	x						x			x							x				x	x	x	x				
6	Ti Fork Non-tapered straight legs with flat inverted-T crown		x						x				x						x			x	x		x				
7	Steel Fork Non-tapered straight legs with flat inverted-T crown			x						x				x						x		x	x	x	x				
8	Carbon Fiber Fork Non-tapered straight legs with flat inverted-T crown																									x	x	x	x
9	Al Fork Tapered straight legs with V crown w/o bolts w threaded steerer	x			x										x			x				x	x	x	x				
10	Ti Fork Tapered straight legs with V crown w/o bolts w threaded steerer	x	x			x										x			x			x	x		x				
11	Steel Fork Tapered straight legs with V crown w/o bolts w threaded steerer	x		x			x										x			x		x	x	x	x				
12	Carbon Fiber Fork Tapered straight legs with V crown w/o bolts w threaded steerer	x																								x	x	x	x
13	Al Fork Tapered straight legs with V crown w bolts w threaded steerer	x			x						x				x			x				x	x	x	x				
14	Ti Fork Tapered straight legs with V crown w bolts w threaded steerer		x			x							x			x			x			x	x		x				
15	Steel Fork Tapered straight legs with V crown w bolts w threaded steerer	x		x			x							x			x			x		x	x	x	x				
16	Carbon Fiber Fork Tapered straight legs with V crown w bolts w threaded steerer	x																								x	x	x	x
17	Al Fork Air sprung oil-damped	x			x			x			x							x				x	x	x	x				
18	Ti Fork Air sprung oil-damped		x			x			x				x						x			x	x		x				
19	Steel Fork Air sprung oil-damped			x			x			x				x						x		x	x	x	x				
20	Carbon Fiber Fork Air sprung oil-damped																									x	x	x	x

Appendix B3 Handle Bar Feature-Options Available With MyBike

	Handle Bar Options \ Machines Required	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Drilling Al tool	Drilling Ti tool	Drilling Steel tool	Welding Al	Welding Ti	Welding Steel	Bending - single bend HandB	Bending - double bend HandB	Surface finishing	Painting	Carbon Fiber moulding/Handle bar	Pressurized heating Chamber for CF moul	Assembly & gluing CF parts	Polishing & painting CF parts
1	Al Single piece handle bar w/o cross bar	x			x									x		x	x				
2	Ti Single piece handle bar w/o cross bar		x			x								x		x					
3	Steel Single piece handle bar w/o cross bar			x			x							x		x	x				
4	Carbon Fiber Single piece handle bar w/o cross bar																	x	x	x	x
5	Al Single piece handle bar w bolted cross bar	x			x			x						x		x	x				
6	Ti Single piece handle bar w bolted cross bar		x			x			x					x		x					
7	Steel Single piece handle bar w bolted cross bar			x			x			x				x		x	x				
8	Carbon Fiber Single piece handle bar w bolted cross bar																	x	x	x	x
9	Al Single piece handle bar w welded cross bar	x			x						x			x		x	x				
10	Ti Single piece handle bar w welded cross bar		x			x						x		x		x					
11	Steel Single piece handle bar w welded cross bar			x			x						x	x		x	x				
12	Carbon Fiber Single piece handle bar w cross bar																	x	x	x	x
13	Al Three piece handle bar w welded cross bar & tapered handles	x			x						x			x		x	x				
14	Ti Three piece handle bar w welded cross bar& tapered handles		x			x						x		x		x					
15	Steel Three piece handle bar w welded cross bar & tapered handles			x			x						x	x		x	x				
16	Carbon Fiber Three piece handle bar w cross bar & tapered handles																	x	x	x	x
17	Al Double bent Two piece handle bar	x			x										x	x	x				
18	Ti Double bent Two piece handle bar		x			x									x	x	x				
19	Steel Double bent Two piece handle bar			x			x								x	x	x				
20	Carbon Fiber Double bent Two piece handle bar																	x	x	x	x

Appendix B4 Wheel Feature-Options Available with MyBike

	Wheel Options \ Machines Required	Alloy Saw	Mmachine alloy milling tool	Welding alloy	Bending Rim Class A	Bending Rim Class B	Surface finishing	Painting	Wheel Assembly	Carbon Fiber moulding/Wheel w spokes	Carbon Fiber moulding/Spokeless wheel	Pressurized heating Chamber for CF moulds	Assembly & gluing CF parts	Polishing & painting CF parts
1	Size AX, Y spoke alloy wheel	x	x	x	x		x	x	x					
2	Size BX, Y spoke alloy wheel	x	x	x		x	x	x	x					
3	Size A_3X, Y spoke Carbon Fiber wheel								x	x		x	x	x
4	Size B_3X, Y spoke Carbon Fiber wheel								x	x		x	x	x
5	Size A_3X spokeless Carbon Fiber wheel										x	x	x	x
6	Size B_3X spokeless Carbon Fiber wheel										x	x	x	x

Appendix B5 Pedal Feature-Options Available with MyBike

	Pedal Options \ Machines Required	Mmachine Mg milling tool	Mmachine Al milling tool	Mmachine Plastic milling tool	Drilling Al tool	Drilling Mg tool	Drilling Plastic tool	Casting Mg pedals	Casting Al pedals	Al Extrusion	Knurling for Al	Injection moulding pedals	Pedal Assembly
1	Cast & Machined Al pedals w/o knurling		x		x				x				x
2	Cast & Machined Al pedals w knurling		x		x				x		x		x
3	Cast & Machined Mg pedals w/o knurling	x				x		x					x
4	Extruded Al pedals				x					x			x
5	Plastic pedals			x			x					x	x

Appendix C The other dataset

Appendix C1 Recyclability, Manufacturing Time, and Development Cost of all the components

Components	Recyclability	Manufacturing Time(h)	Development Cost ($)
Pedal 1	0.75	0.1	10000
Pedal 2	0.75	0.12	15000
Pedal 3	0.71	0.1	13000
Pedal 4	0.75	0.08	15600
Pedal 5	0.8	0.08	10000
Wheel 1	0.7	0.13	20000
Wheel 2	0.7	0.14	21000
Wheel 3	0.5	0.21	24000
Wheel 4	0.5	0.23	24300
Wheel 5	0.5	0.28	27000
Wheel 6	0.5	0.31	28000
Handle bar 1	0.75	0.15	18000
Handle bar 2	0.82	0.2	22000
Handle bar 3	0.72	0.15	13400
Handle bar 4	0.5	0.22	20000
Handle bar 5	0.75	0.18	20000
Handle bar 6	0.82	0.23	24000
Handle bar 7	0.72	0.18	15000
Handle bar 8	0.5	0.28	21000
Handle bar 9	0.75	0.2	19000
Handle bar 10	0.82	0.25	23000
Handle bar 11	0.72	0.2	14000
Handle bar 12	0.5	0.3	21000
Handle bar 13	0.75	0.34	24000
Handle bar 14	0.82	0.41	26000
Handle bar 15	0.72	0.34	17000
Handle bar 16	0.5	0.49	24000
Handle bar 17	0.75	0.31	28000
Handle bar 18	0.82	0.45	30000
Handle bar 19	0.72	0.29	20000
Handle bar 20	0.5	0.47	25000
Fork 1	0.75	0.32	20000
Fork 2	0.82	0.48	23000
Fork 3	0.72	0.33	15000
Fork 4	0.5	0.51	22000

Fork 5	0.75	0.34	21000
Fork 6	0.82	0.49	24000
Fork 7	0.72	0.35	16000
Fork 8	0.5	0.5	24000
Fork 9	0.75	0.35	22000
Fork 10	0.82	0.55	25000
Fork 11	0.72	0.38	17000
Fork 12	0.5	0.56	24000
Fork 13	0.75	0.36	26000
Fork 14	0.82	0.52	28000
Fork 15	0.72	0.35	18000
Fork 16	0.5	0.59	27000
Fork 17	0.75	0.45	30000
Fork 18	0.82	0.65	35000
Fork 19	0.72	0.48	30000
Fork 20	0.5	0.7	34000
Frame 1	0.75	0.48	35000
Frame 2	0.82	0.68	40000
Frame 3	0.72	0.45	30000
Frame 4	0.5	0.7	37000
Frame 5	0.75	0.42	32000
Frame 6	0.82	0.63	37000
Frame 7	0.72	0.41	28000
Frame 8	0.5	0.62	34000
Frame 9	0.75	0.39	30000
Frame 10	0.82	0.6	34000
Frame 11	0.72	0.35	25000
Frame 12	0.5	0.62	30010
Frame 13	0.75	0.54	43000
Frame 14	0.5	0.72	47000
Frame 15	0.75	0.5	48000
Frame 16	0.5	0.7	52000

Appendix C2 Questionnaire for AHP

Identifying Factors for Sustainability Assessment for Bicycle configuration

1. Sustainability Assessment

Sustainability includes economic, environmental and societal factors. If you want to design a **sustainable bicycle**, which factor would you give weight to? Economic factors include cost of raw material, cost of design and development, cost of facility, labor cost and energy cost. Environmental factors include CO2 emission and energy consumption. Societal factors includes customer satisfaction, service, safety, disassemblability, and recyclability Please pick a number and circle it to represent their importance when compared pairwise.

Economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental
Economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Societal
Environmental	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Societal

2. Societal Sustainability Assessment

Societal factors include customer satisfaction, service, safety, disassemblability, and recyclability. Which factor do you think is more important in these societal factors? You are required to identify the relative importance of these factors.

Please pick a number and circle it to represent their importance when compared pairwise.

Customer satisfaction	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Service
Customer satisfaction	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety
Customer satisfaction	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Disassembly
Customer satisfaction	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Recyclability
Service	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety
Service	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Disassembly
Service	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Recyclability
Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Disassembly
Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Recyclability
Disassembly	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Recyclability

Table 24. The Fundamental Scale for Making Judgments

1	Equal
2	Between Equal and Moderate
3	Moderate
4	Between Moderate and Strong
5	Strong
6	Between Strong and Very Strong
7	Very Strong
8	Between Very Strong and Extreme
9	Extreme

Appendix C3 Other Data for The Manufacturing Process of All the Components

	Variable (Frame) \ Machines Required	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Mmachine Al milling tool	Mmachine Ti milling tool	Mmachine Steel milling tool	Drilling Al tool	Thread cutting Al	Thread cutting Ti	Thread cutting Steel	Welding Al	Welding Ti	Welding Steel	Bending Frame parts	Frame holding fixture	Crosstrac frame fixture	Al Stamping/Forming	Surface finishing	Painting	Frame Assembly	Carbon Fiber moulding/Frame	Pressurized heating Chamber for CF moul	Assembly & gluing CF parts	Polishing & painting CF parts
1	Productivity(1000)/day	3	2.8	3	3.4	2.9	3.4	4	3.2	2.9	4	1.9	2.5	3.4	2.3	4.3	2.1	3.5	2.4	5.2	3.4	2.4	3.4	2	2.4	3.4	3.1	4
2	Cost of the machine(10000$)	1	2	1	2	3.2	2	1.8	3	1.8	3.2	2	1.8	1.3	3	4.5	2.5	3.8	1.7	5	3.5	3	3.9	1.5	2.8	1	2	1.6
3	Safety coefficient	9	8	9	8	7	8	7	6	7	7	8	7	8	7	6	7	7	9	8	8	8	9	9	8	8	8	8

	Variable (Fork) \ Machines Required	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Mmachine Al milling tool	Mmachine Ti milling tool	Mmachine Steel milling tool	Drilling Al tool	Drilling Mg tool	Drilling Ti tool	Drilling Steel tool	Thread cutting Al	Thread cutting Ti	Thread cutting Steel	Welding Al	Welding Ti	Welding Steel	Bending Fork/Frame parts	Fork holding fixture	Surface finishing	Painting	Fork Assembly	Carbon Fiber moulding/Fork	Pressurized heating Chamber for CF moulds	Assembly & gluing CF parts	Polishing & painting CF parts
1	Productivity(1000)/day	3	2.8	3	3.4	2.9	3.4	4	3.2	2	1.9	3.2	3.8	4	2	1.3	2.4	3.1	2.5	2.9	3	3.1	2.3	3	3.2	2.6	3.1	1.8	4
2	Cost of the machine(10000$)	1	2	1	2	3.2	2	1.8	3	1.8	3.2	2.4	3.5	2.5	2	4	2.1	3	5	3.2	4	2	2.4	2	1.5	2.8	1.9	2	2.3
3	Safety coefficient	9	8	9	8	7	8	7	6	7	7	8	7	7	8	7	8	7	6	7	7	8	8	8	8	8	7	8	8

	Machines Required / Variable (Handle Bar)	Al Saw	Ti Saw	Steel Saw	Lathe Al tool	Lathe Ti tool	Lathe Steel tool	Drilling Al tool	Drilling Ti tool	Drilling Steel tool	Welding Al	Welding Ti	Welding Steel	Bending - single bend HandB	Bending - double bend HandB	Surface finishing	Painting	Carbon Fiber moulding/Handle bar	Pressurized heating Chamber for CF moul	Assembly & gluing CF parts
1	Productivity(1000)/day	3	2.8	3	3.4	2.9	3.4	4	3.2	1.9	3	2.8	3.9	4.2	2.8	2.5	1.7	4.2	3.1	2
2	Cost of the machine(10000$)	2	1	2	3.2	4.5	3	3	4.8	3.1	3	4.9	3.1	3.4	4.5	2	2.5	2	2.1	1.5
3	Safety coefficient	9	8	9	8	7	8	7	6	7	7	8	7	7	8	7	8	7	6	7

	Machines Required / Variable (Wheel)	Alloy Saw	Mmachine alloy milling tool	Welding alloy	Bending Rim Class A	Bending Rim Class B	Surface finishing	Painting	Wheel Assembly	Carbon Fiber moulding/Wheel w spokes	Carbon Fiber moulding/Spokeless wheel	Pressurized heating Chamber for CF moulds	Assembly & gluing CF parts	Polishing & painting CF parts
1	Productivity(1000)/day	2	2.2	1.9	4	3.5	2.9	3	3.2	2	2.2	4	5	5.2
2	Cost of the machine(10000$)	2.3	3	4.2	3.2	3.3	2	2.4	2.5	2.7	3	2.2	1.9	2.4
3	Safety coefficient	8	7	7	7	7	8	8	8	8	7	8	8	8

	Machines Required / Variable (Pedal)	Mmachine Mg milling tool	Mmachine Al milling tool	Mmachine Plastic milling tool	Drilling Al tool	Drilling Mg tool	Drilling Plastic tool	Casting Mg pedals	Casting Al pedals	Al Extrusion	Knurling for Al	Injection moulding pedals	Pedal Assembly
1	Productivity(1000)/day	1.8	2	3.4	2.9	3.2	4	2.3	3.2	2.9	4	2.8	4
2	Cost of the machine(10000$)	2.3	3	1	3	3.2	1.3	3.5	3.8	3.1	1.4	2	1
3	Safety coefficient	7	7	8	7	6	8	7	7	7	7	7	8

Appendix C4 The Cost of Raw Material and Labor Cost per Hour

Material	Aluminum	Iron	Titanium	Carbon fiber	Plastic	Magnesium
Price($/Kg)	2.048	0.912	25	20	2.5	3.2

Cost	**Price($/Hour)**
Labor Cost	**20**

Reference

Agard, B., & Kusiak*, A. (2004). Data-mining-based methodology for the design of product families. International Journal of Production Research, 42(15), 2955-2969.

Akao, Y. (1994). Development history of quality function deployment. The Customer Driven Approach to Quality Planning and Deployment. Minato, Tokyo 107 Japan: Asian Productivity Organization (p. 339). ISBN 92-833-1121-3.

Allada, V., & Lan, J. (2002, January). New modules launch planning for evolving modular product families. In ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 349-358). American Society of Mechanical Engineers.

Ardente, F., Beccali, G., & Cellura, M. (2003). Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS". Ecological Modelling, 163(1), 101-118.

Arena, U., Mastellone, M. L., & Perugini, F. (2003). The environmental performance of alternative solid waste management options: a life cycle assessment study. Chemical Engineering Journal, 96(1), 207-222.

Azapagic, A., Millington, A., & Collett, A. (2006). A methodology for integrating sustainability considerations into process design. Chemical Engineering Research and Design, 84(6), 439-452.

Badurdeen, F., Iyengar, D., Goldsby, T. J., Metta, H., Gupta, S., & Jawahir, I. S. (2009). Extending total life-cycle thinking to sustainable supply chain design. International Journal of Product Lifecycle Management, 4(1), 49-67.

Badurdeen, F. (2009). is cited for the life-cycle figure.

Badurdeen, F. (2012). Working paper at the University of Kentucky.

Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., ... & Wilson, H. (2007). State-of-the-art in product-service systems. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221(10), 1543-1552.

Boon, J. E., ISAACS, J. A., & GUPTA, S. M. (2002). Economic sensitivity for end of life planning and processing of personal computers. Journal of Electronics Manufacturing, 11(01), 81-93.

Bouchereau, V., & Rowlands, H. (2000). Methods and techniques to help quality function deployment (QFD). Benchmarking: An International Journal, 7(1), 8-20.

Cerri, D., Taisch, M., & Terzi, S. (2014). Proposal of a Model for Life Cycle Optimization of Industrial Equipment. Procedia CIRP, 15, 479-483.

Chan, J. W., & Tong, T. K. (2007). Multi-criteria material selections and end-of-life product strategy: Grey relational analysis approach. Materials & Design, 28(5), 1539-1546.

Chiu, M. C., & Chu, C. H. (2012). Review of sustainable product design from life cycle perspectives. International Journal of Precision Engineering and Manufacturing, 13(7), 1259-1272.

Chu, C. H., Luh, Y. P., Li, T. C., & Chen, H. (2009). Economical green product design based on simplified computer-aided product structure variation. Computers in Industry, 60(7), 485-500.

Clark, W. C., & Dickson, N. M. (2003). Sustainability science: the emerging research program. Proceedings of the national academy of sciences, 100(14), 8059-8061.

Collier, D. A. (1981). The measurement and operating benefits of component part commonality. Decision Sciences, 12(1), 85-96.

Coulter, S., Bras, B., Winslow, G., & Yester, S. (1998). Designing for material separation: lessons from automotive recycling. Journal of Mechanical Design, 120(3), 501-509.

D'Souza, B., & Simpson∗, T. W. (2003). A genetic algorithm based method for product family design optimization. Engineering Optimization, 35(1), 1-18.

Devanathan, S., Ramanujan, D., Bernstein, W. Z., Zhao, F., & Ramani, K. (2010). Integration of sustainability into early design through the function impact matrix. Journal of Mechanical Design, 132(8), 081004.

Du, X., Jiao, J., & Tseng, M. M. (2001). Architecture of product family: fundamentals and methodology. Concurrent Engineering, 9(4), 309-325.

Erixon, G., & Ostgren, B. (1993). Synthesis and evaluation tool for modular designs. In International conference on engineering design (pp. 898-905).

Erlandsson, A., Erixon, G., & Ostgren, B. (1992). Product modules-the link between QFD and DFA. In The International Forum on Product Design for Manufacture and Assembly, Newport, RI.

Fellini, R., Kokkolaras, M., Michelena, N., Papalambros, P., Perez-Duarte, A., Saitou, K., & Fenyes, P. (2004). A sensitivity-based commonality strategy for family products of mild variation, with application to automotive body structures. Structural and Multidisciplinary Optimization, 27(1-2), 89-96.

Ferrão, P., & Amaral, J. (2006). Design for recycling in the automobile industry: new approaches and new tools. Journal of Engineering Design, 17(5), 447-462.

Gaha, R., Benamara, A., & Yannou, B. (2013). Ecodesigning with CAD Features: Analysis and Proposals. Advances in Mechanical Engineering, 2013.

Giudice, F., La Rosa, G., & Risitano, A. (2005). Materials selection in the life-cycle design process: a method to integrate mechanical and environmental performances in optimal choice. Materials & Design, 26(1), 9-20.

Grant, R. M. (2010). Contemporary strategy analysis and cases: text and cases. John Wiley & Sons.

Güngör, A. (2006). Evaluation of connection types in design for disassembly (DFD) using analytic network process. Computers & Industrial Engineering, 50(1), 35-54.

Guo, F., & Gershenson, J. K. (2004, January). A comparison of modular product design methods based on improvement and iteration. In ASME 2004 International Design

Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 261-269). American Society of Mechanical Engineers.

Gaha, R., Benamara, A., & Yannou, B. (2013). Ecodesigning with CAD Features: Analysis and Proposals. Advances in Mechanical Engineering, 2013.

Haapala, K. R., Zhao, F., Camelio, J., Sutherland, J. W., Skerlos, S. J., Dornfeld, D. A., ... & Rickli, J. L. (2013). A review of engineering research in sustainable manufacturing. Journal of manufacturing Science and Engineering, 135(4), 041013.

Hernandez, G., Allen, J. K., & Mistree, F. (2003). Platform design for customizable products as a problem of access in a geometric space. Engineering Optimization, 35(3), 229-254.

Hölttä-Otto, K., & Otto, K. (2006). Platform concept evaluation. In Product Platform and Product Family Design (pp. 49-72). Springer US.

Hölttä, K., Tang, V., & Seering, W. P. (2003). Modularizing product architectures using dendrograms. In DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm.

Houe, R., & Grabot, B. (2007). Knowledge modeling for eco-design. Concurrent Engineering, 15(1), 7-20.

Ilgin, M. A., & Gupta, S. M. (2010). Environmentally conscious manufacturing and product recovery (ECMPRO): a review of the state of the art. Journal of environmental management, 91(3), 563-591.

Jaafar, I. H., Venkatachalam, A., Joshi, K., Ungureanu, A. C., De Silva, N., Dillon Jr, O. W., ... & Jawahir, I. S. (2007). Product design for sustainability: a new assessment methodology and case studies. Environmentally Conscious Mechanical Design, 5, 25.

Jawahir, I. S. (2008, August). Beyond the 3R's: 6R Sustainability Concepts for Next Generation Manufacturing. In Keynote paper presented at IIT MMAE Symposium on Sustainability and Product Development.

Jiao, J., & Tseng, M. M. (2000). Understanding product family for mass customization by developing commonality indices. Journal of Engineering Design, 11(3), 225-243.

Jiao, J. R., Simpson, T. W., & Siddique, Z. (2007). Product family design and platform-based product development: a state-of-the-art review. Journal of intelligent Manufacturing, 18(1), 5-29.

Kar, A. M. (2007). A cost modeling approach using learning curves to study the evolution of technology (Doctoral dissertation, Massachusetts Institute of Technology).

Khan, F. I., Sadiq, R., & Veitch, B. (2004). Life cycle iNdeX (LInX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production, 12(1), 59-76.

Khasreen, M. M., Banfill, P. F., & Menzies, G. F. (2009). Life-cycle assessment and the environmental impact of buildings: a review. Sustainability, 1(3), 674-701.

Kimura, F., Kato, S., Hata, T., & Masuda, T. (2001). Product modularization for parts reuse in inverse manufacturing. CIRP Annals-Manufacturing Technology, 50(1), 89-92.

Knight, W. A., & Sodhi, M. (2000). Design for bulk recycling: analysis of materials separation. CIRP Annals-Manufacturing Technology, 49(1), 83-86.

Komoto, H., & Tomiyama, T. (2008). Integration of a service CAD and a life cycle simulator. CIRP Annals-Manufacturing Technology, 57(1), 9-12.

Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for ‘X’: concepts, applications, and perspectives. Computers & Industrial Engineering, 41(3), 241-260.

Kuo, T. C. (2006). Enhancing disassembly and recycling planning using life-cycle analysis. Robotics and Computer-Integrated Manufacturing, 22(5), 420-428.

Kwak, M., & Kim, H. M. (2011). Assessing product family design from an end-of-life perspective. Engineering Optimization, 43(3), 233-255.

Kwak, M. J., Hong, Y. S., & Cho, N. W. (2009). Eco-architecture analysis for end-of-life decision making. International Journal of Production Research, 47(22), 6233-6259.

Li, J., Wu, Z., & Zhang, H. C. (2008). Application of neural network on environmental impact assessment tools. International Journal of Sustainable Manufacturing, 1(1), 100-121.

Lin, F. (2006). A methodology for material selection in green design with toxic impact concern. ProQuest.

Madu, C. N., Kuei, C., & Madu, I. E. (2002). A hierarchic metric approach for integration of green issues in manufacturing: a paper recycling application. Journal of environmental management, 64(3), 261-272.

Martin, M. V., & Ishii, K. (1997, September). Design for variety: development of complexity indices and design charts. In Proceedings of (pp. 14-17).

Masanet, E., & Horvath, A. (2007). Assessing the benefits of design for recycling for plastics in electronics: A case study of computer enclosures. Materials & design, 28(6), 1801-1811.

Masui, K., Sakao, T., Kobayashi, M., & Inaba, A. (2003). Applying quality function deployment to environmentally conscious design. International Journal of Quality & Reliability Management, 20(1), 90-106.

Mattson, C. A., & Magleby, S. P. (2001). The influence of product modularity during concept selection of consumer products. In Proceedings of the ASME DETC Design Theory and Methodology Conference, Pittsburgh, PA, Sept (pp. 9-12).

Mayyas, A., Qattawi, A., Omar, M., & Shan, D. (2012). Design for sustainability in automotive industry: A comprehensive review. Renewable and Sustainable Energy Reviews, 16(4), 1845-1862.

McAdams, D. A., & Wood, K. L. (2002). A quantitative similarity metric for design-by-analogy. Journal of mechanical design, 124(2), 173-182.

Messac, A., Martinez, M. P., & Simpson, T. W. (2002). A penalty function for product family design using physical programming. ASME Journal of Mechanical Design, 124(2), 164-172.

Messac, A., Martinez, M. P., & Simpson, T. W. (2002). Effective product family design using physical programming. Engineering Optimization, 34(3), 245-261.

Nelson, S. A., Parkinson, M. B., & Papalambros, P. Y. (2001). Multicriteria optimization in product platform design. Journal of Mechanical Design, 123(2), 199-204.

Newcomb, P. J., Bras, B., & Rosen, D. W. (1998). Implications of modularity on product design for the life cycle. Journal of Mechanical Design, 120(3), 483-490.

Pine, B. J. (1999). Mass customization: the new frontier in business competition. Harvard Business Press.

Rai, R., & Allada, V. (2003). Modular product family design: agent-based Pareto-optimization and quality loss function-based post-optimal analysis. International Journal of Production Research, 41(17), 4075-4098.

Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., ... & Thurston, D. (2010). Integrated sustainable life cycle design: a review. Journal of Mechanical Design, 132(9), 091004.

Robertson, D., & Ulrich, K. (1998). Planning for product platforms. Sloan management review, 39(4).

Rojas Arciniegas, A. J., & Kim, H. M. (2012). Incorporating security considerations into optimal product architecture and component sharing decision in product family design. Engineering Optimization, 44(1), 55-74.

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. Management science, 32(7), 841-855.

Sakao, T. (2007). A QFD-centred design methodology for environmentally conscious product design. International Journal of Production Research, 45(18-19), 4143-4162.

Shuaib, M., Seevers, D., Zhang, X., Badurdeen, F., Rouch, K. E., & Jawahir, I. S. (2014). Product Sustainability Index (ProdSI). Journal of Industrial Ecology, 18(4), 491-507.

Siddique, Z., Rosen, D. W., & Wang, N. (1998, September). On the applicability of product variety design concepts to automotive platform commonality. In ASME Design Engineering Technical Conferences-Design Theory and Methodology.

Simpson, T. W. (2004). Product platform design and customization: Status and promise. AI EDAM: Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 18(01), 3-20.

Simpson, T. W., Maier, J. R., & Mistree, F. (2001). Product platform design: method and application. Research in engineering Design, 13(1), 2-22.

Simpson, T. W., Siddique, Z., & Jiao, J. R. (2006). Platform-based product family development. In Product platform and product family design (pp. 1-15). Springer US.

Stoll, H. W. (1988). Design for manufacture, Tool and manufacturing engineers handbook, Vol. 5.

Stoll, H. W. (1990). "Design for Manufacturing." Simultaneous Engineering.

Stone, R. B., Wood, K. L., & Crawford, R. H. (1998, September). A heuristic method to identify modules from a functional description of a product. In Proceedings of DETC98 (pp. 1-11).

Tang, Y., Zhou, M., Zussman, E., & Caudill, R. (2002). Disassembly modeling, planning, and application. Journal of Manufacturing Systems, 21(3), 200-217.

Thevenot, H. J., & Simpson, T. W. (2006). Commonality indices for assessing product families. In Product platform and product family design (pp. 107-129). Springer US.

Tyagi, S., Yang, K., Tyagi, A., & Verma, A. (2012). A fuzzy goal programming approach for optimal product family design of mobile phones and multiple-platform architecture. Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, 42(6), 1519-1530.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. Research policy, 24(3), 419-440.

Utterback, J. M., & Meyer, M. H. (1993). The product family and the dynamics of core capability. Sloan management review, 34(Spring), 29-47.

Welp, E. G., Meier, H., Sadek, T., & Sadek, K. (2008). Modelling approach for the integrated development of industrial product-service systems. In Manufacturing Systems and Technologies for the New Frontier (pp. 525-530). Springer London.

Wijekoon, K. H. T. (2011). Modeling and optimization to evaluate sustainability performance of customizable product service systems.

Wright, E., Azapagic, A., Stevens, G., Mellor, W., & Clift, R. (2005). Improving recyclability by design: a case study of fibre optic cable. Resources, conservation and recycling, 44(1), 37-50.

Xu, Q. L., Ong, S. K., & Nee, A. Y. C. (2007). Evaluation of product performance in product family design re-use. International Journal of Production Research, 45(18-19), 4119-4141.

Yan, W., Chen, C. H., & Chang, W. (2009). An investigation into sustainable product conceptualization using a design knowledge hierarchy and Hopfield network. Computers & Industrial Engineering, 56(4), 1617-1626.

Zamirowski, E. J., & Otto, K. N. (1999). Identifying product family architecture modularity using function and variety heuristics. In 11th International Conference on Design Theory and Methodology, ASME, Las Vegas.

Zhang, X., Lu, T., Shuaib, M., Rotella, G., Huang, A., Feng, S. C., ... & Jawahir, I. S. (2012). A metrics-based methodology for establishing product sustainability index (ProdSI) for manufactured products. In Leveraging technology for a sustainable world (pp. 435-441). Springer Berlin Heidelberg.

Zhou, C. C., Yin, G. F., & Hu, X. B. (2009). Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. Materials & Design, 30(4), 1209-1215.

VITA

Name
Tian Lan

Place of Birth
Shandong, China

Education
Master Student, Mechanical Engineering, University of Kentucky, Lexington, KY (May, 2015)
Master Student, Statistics, University of Kentucky, Lexington, KY (May, 2015)
B.E., Material Processing and Control Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China (July, 2010)

Professional Experience
- Teaching Assistant (August 2013 – May 2014, January 2015 – May 2015)
  Department of Statistics, University of Kentucky, Lexington, KY
- Decision Science Professional Intern (June 2014 – January 2015)
  Revenue Management & Analytics, The Walt Disney Company, Orlando, FL
- Intern (January 2013 – June 2013)
  Center for Applied Energy Research, University of Kentucky, Lexington, KY
- Research Assistant (May 2012 – August 2012)
  Department of Mechanical Engineering, University of Kentucky, Lexington, KY
- Teaching Assistant (August 2010 – May 2012)
  Department of Mechanical Engineering, University of Kentucky, Lexington, KY

Synergistic Activities
- Session Chair: Sustainability Metrics and Policy Making, IIE Annual Conference and Expo 2013, May 18 - 22, San Juan, Puerto Rico

Presentations
- Tian Lan, Fazleena Badurdeen, "Mathematical Modeling for Platform-based Product Configuration Considering Total Life-cycle Sustainability". Presented at The Industrial and Systems Engineering Research Conference, May 18 - 22, 2013, San Juan, Puerto Rico