Optimizing Sustainable Product Development

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ABSTRACT

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Global warming, which is caused by increasing concentrations of carbon emissions, mainly results from human activities, such as fossil fuel burning and deforestation. In order to alleviate global warming and its adverse effects, many countries including the United States and the European Union members have attempted to enact legislation or design market-based carbon trading mechanisms to control carbon emissions. Analyzing the impact of such governmental legislation on developing products has been studied, both in theory and practice. Firms need to incorporate governmental regulations and consider environmental issues and reduced carbon emission in their product development processes, this thesis presents three models for sustainable product development. All models consider environmental issues and cost for the whole life cycle of the product, from the extraction of raw materials to the end of life of the product. Three group of customer requirements are defined as cost, quality and sustainability. The objective of the models is to maximize utility to the customers for these groups of customer requirements. In all three models, three groups of customer requirements are translated to design specifications and the utility of each group is evaluated. The first model is a scoring model to compare between different designs and select the best one; the second model is an optimization model, which provides optimum value for design specifications while maximizing the total utility to the customers for the final design. And finally, the third model is a two-stage stochastic optimization model in which the weights of customer requirements are considered as uncertain parameters. This model also provides the optimum value for design specifications while modeling the weight of customer requirements as an uncertain parameter. The last two models are non-linear, non-convex models with certain conditions and are solved using the Branch-and-Reduce Optimization Navigator methodology. In all three models, Quality Function Deployment is applied to make trade-offs within each group of customer requirements and multi-attribute utility theory is used to make trade-offs between three groups of customer requirements. All three models are applied to a case study, and results show that introducing uncertainty in the parameters increases the total utility by 9.41%, and the optimization model also has the potential to help designers find an optimum design yielding higher customer satisfaction, reducing the time of product development process and making the final design more reliable based on stakeholder's opinions.

Preface

This dissertation has been realized under the co-direction of Professor Nadia Bhuiyan, professor at the Mechanical, Industrial & Arospace Engineering Department of Concordia University. It has been prepared in "Manuscript-based" format. This research was financially supported through a Natural Sciences and Engineering Research Council (NSERC) grant.

The research includes three articles, co-authored by Professor Nadia Bhuiyan. All the contents that are represented in this thesis either have been accepted or submitted for publication in the form of journal articles. In all of the presented articles, I have acted as the principal researcher and performed the mathematical models development, coding the algorithms, analysis and validation of the results, as well as writing of the first drafts of the articles. Professor Nadia Bhuiyan has reviewed and edited the articles to obtain the final version prior to submission.

The first article entitled *"A proposed approach to improve current sustainable product development"*, co-authored by Professor Nadia Bhuiyan, was published in the *Journal of Industrial and Production Engineering* in May 2016.

The second article entitled *"A new model of sustainable product development process for making trade-offs"*, co-authored by Professor Nadia Bhuiyan, was published to the *International Journal of Advanced Manufacturing technology* in September 2016.

The third article entitled *"Making trade-offs to achieve sustainable product development"*, co-authored by Professor Nadia Bhuiyan, was submitted to the *Journal of Cleaner Production* in July 2017.

Dedicated to my beloved Mom & Dad

For their love, endless support and encouragement

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I would like to express my deepest gratitude and appreciation to my adored parents for their ultimate support, patience and encouragement. Their worthwhile support and love during my PhD thesis have encouraged me to do my best to achieve my goal. I do not know how I can express my appreciation to them in words for their ultimate support and grace. I only hope that I have made their support worthwhile, and compensate some parts of their fortitude.
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1. Chapter 1: Introduction

In this chapter, first we provide the motivation for this thesis. Then, we describe the problem studied. The scope and objectives, as well as the thesis organization are provided at the end of the chapter.

1.1. Research motivation

The world is changing rapidly, urbanization and population is growing, as is consumption of natural resources. A changing world means a changing marketplace. This growth in consumption is causing a strain on the environment, and governments have acted on the need to preserve the environment in part through regulations, which require companies to find solutions to address the problem. Companies must therefore find ways to do more with less, while dealing with the rising costs of raw materials, energy and capital equipment. Sustainability, which can be defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1], in addition to environmental benefits, can generate a positive image for businesses and improve economic returns.

Sustainable production includes equipment, materials, and methods that promote the reduction of waste and efficient use of resources (especially non-renewable ones) [2]. It's a departure from the customary manufacturing process that prioritizes profit margins and cost-effectiveness while ignoring environmental impacts. According to the Green Business Bureau, as environmental consciousness grows, customers are requesting more green services and products [3]. Companies that declare the fact they are trying to be sustainable can achieve the favor of like-minded consumers. Their efforts to go green become a part of their marketing campaign through the mention of the sustainability changes that have been made while environmentally conscious customers check labels for products made from recycled materials [4]. Because of this growing consciousness, the market share for sustainable products in a variety of industries has continued to expand. Companies can tap into this market by offering more sustainable services and products.

The financial advantage of implementing sustainability practices is undeniable. Finding the ideal balance of value to the customer versus resources expended is the key to delivering the most profitable results in terms of environmental advantages and revenue generated delivered. Besides the financial advantages, the stringent environmental regulations force industrial companies to reduce adverse environmental impacts caused by their services and products. Therefore, financial advantage, environmental rules and regulations, aside from better brand image, lead companies to design sustainable products and services. Because of the above reasons, we aimed to investigate the development of sustainable products. "Based on the estimation from the EU report, 80-90% of all product-related environmental impacts are determined during the design phase of a product." [5]. Also it is known that up to 80% of product life cycle cost are committed during product development process [6]. Therefore, we focus on the product development process in this research and consider sustainability of the product at this stage of its life cycle.

1.2. Problem description

Since by finalizing the design almost 80% of sustainability of the product will be fixed, considering environmental impact should be done in product development process before the final design. In the literature, there are many tools and methods for considering environmental issues in the product development (PD) process in order to make the new product sustainable. However, our literature review shows there are still some barriers and limitations in existing tools and methods. These limitations are as follows which are further explained in Chapter 2.3.3:

1. Weak support of trade-offs;
2. Difficulty in learning, understanding, and using the tools;
3. Weak connection with the PD process;
4. Lack of life cycle thinking;
5. Lack of holistic methods;
6. Lack of communication.

In this research, we aimed to add sustainability at the first step of PD and check it throughout the process until the final product is designed. For this purpose, making trade-offs is modeled and supported during the PD process, and a holistic model which includes the whole life cycle of the product presented. Customer requirements and design specifications are modeled in order to optimize the utility of three groups of customer requirements. Three groups of customer requirements are defined: Cost Requirements, Environmental Requirements and Quality Requirements. Each group has its own utility, based on which the final utility is calculated. Environmental issues for the life cycle of the product is considered as a group of customer requirements and translated into design specifications to optimize their final values. Finally, the weights of customer requirements are considered as stochastic parameters in order to increase the accuracy and the realism of the model versus a deterministic model. This model helps a designer start with an initial value of a design specification, which maximizes utility of customer requirements and tracks the effect of any changes during the PD process on total utility.

1.2.1. Scope and objectives

According to existing gaps in the literature, our general objective is to develop an optimization model to maximize the total utility of the customer requirements while considering sustainability in product design by modeling design specifications and customer requirements.

The specific objectives of this dissertation are described as follows:

1. To propose a comprehensive literature review on sustainable PD.
2. To consider sustainability for the whole life cycle of the product during the PD process.
3. To support trade-offs for designers during the PD process.
4. To propose a sustainability method that is completely integrated with the PD process.
5. To formulate a mathematical programming model to maximize total utility of the customer requirements.
6. To add more realism into model by considering weights of customer requirements as stochastic parameters.

1.2.2. Organization of the thesis

The remainder of this thesis is organized as follows. Chapter 2 is dedicated to a comprehensive literature review and develops a scoring model to improve current sustainable PD tools and methods. The scoring model can compare different concepts during the concept development phase of D. It provides a value for the utility of each concept for customers. Chapter 3 finds the optimum concept, which has maximum utility for customers. An optimization model is proposed; its solution results in optimum values for design specifications. Therefore, designers can use these as initial values to start, and during PD, if they face any constraints which force them to change any design specification, they can determine its effect on the others and adapt the concept to meet the constraint. The final model is non-convex non-linear with certain conditions, to which the BARON methodology is applied in order to solve it. It is applied to a case study and results are presented. Chapter 4 attempts to provide a stochastic optimization model by considering the weights of customer requirements as uncertain parameters. A two–stage stochastic optimization model is proposed and applied to the same case study used in the previous chapter. Results were compared with the deterministic model. Finally, Chapter 5 summarizes this dissertation by providing some concluding remarks and recommendations for future works.

2. Chapter 2: A proposed approach to improve current sustainable product development

This chapter consists of the article entitled *A proposed approach to improve current sustainable product development*, published in the Journal of Industrial and Production Engineering [7].

ABSTRACT

Systematic consideration of environmental aspects within the early stages of product development (PD) can be considered highly significant in order for the overall environmental performance of the product to be improved. Many methods and tools have been developed aiming to enable this consideration and provide the properties that need to be considered and improved. This article provides an overview of some well-known and more applicable tools and methods that have been developed and are available today. The identified tools are generally classified in two groups: Guidelines and Analytical tools. The limitations and barriers of current tools are assessed and categorized and two areas for work are proposed in order to address current limitations in the existing literature. One of the areas is followed and a scoring model is proposed as a new tool for sustainable PD.

2.1. Introduction

These days, people recognize that besides profits, there are other elements in the long-term success of companies and economies that are important to consider. Issues such as the future of generations to come and the future of the planet are gaining more significance. These concerns are measured as the triple bottom line (TBL), which stands for people, profit and the planet [8, 9, 10].

The growth of industrial products is dramatic and should be considered in the implementation of TBL. Product development (PD), as the first step of creating a product, has a great influence on its sustainability as by the end of the PD process, the sustainability attributes of the product are largely fixed. Early decisions in PD can have a significant or even dominant impact on the sustainability of product realization [11]. Therefore, adding sustainability to PD is increasingly becoming an important issue for companies [12]. Considering the environmental aspects of a product, PD becomes sustainable PD. Sustainable PD focuses on reducing or eliminating environmental impacts over a product life cycle by incorporating environmental considerations into product design. In many cases when environmental aspects are integrated into PD, it leads to synergies with other business interests, such as image improvement, new market opportunities and very often, cost reductions. Indeed, many organizations have faced economic benefits when environmental considerations were considered in the design process [13, 9]. Numbers of methods and tools have been developed to assist in integrating environmental aspects into the PD process.

This research assesses current tools and methods for sustainable product development in order to discover barriers and limitations of them and propose a model to meet some of current barriers. Sustainable PD is defined and the importance of life cycle thinking is highlighted. The ways to improve current tools and methods are considered and appropriate solutions are analyzed to be recommended for future work. Six major reasons for poor application of current tools are recognized and two ways for development are introduced, from which one is pursued. The literature review on which we report here is based on 160 articles in the field of sustainable design, sustainable product design, sustainable PD and sustainable tools and methods for PD. Publications were selected through searching various sources from the engineering, management, and policy studies disciplines. It should be mentioned that the number of publications that exist is large and consequently it was not possible to analyse all articles or books. Thus a screening process of the available material was needed in order to select the publications that should be considered for the study.

The article is organized as follows: the next section describes the product life cycle; Section 3 presents a discussion of sustainable PD, tools and methods for sustainable PD. Section 4 provides barriers and limitation of current tools and methods, solutions to meet current barriers and limitations are discussed in Section 5, one of the solutions is pursued and a scoring model is proposed, and finally conclusions and future work are presented in section 6.

2.2. Product Life Cycle

A product life cycle is the successive and interconnected stages of a product system, from the extraction of raw materials or natural resources, to manufacturing, use and end of life. A product life cycle is the successive and interconnected stages of a product system, from the extraction of raw materials or natural resources, to manufacturing, use and end of life. Life cycle thinking means "widening views and expands the traditional focus on manufacturing processes to incorporate various aspects associated with a product over its entire life cycle" [14].

Essentially everything that is created goes through several key life cycle stages: extraction of raw materials, manufacturing, distribution and packaging, use and end of life (recycle, landfill or incinerate) [15]. Figure 1 is a general diagram which shows the circular nature of material flows through a product life cycle.

Each of the life cycle stages has a variety of inputs such as material, energy and water and outputs such as solid waste, emissions, products and by-products. These can be identified and assessed for their environmental impacts at each of the life cycle stages that products and materials go through.

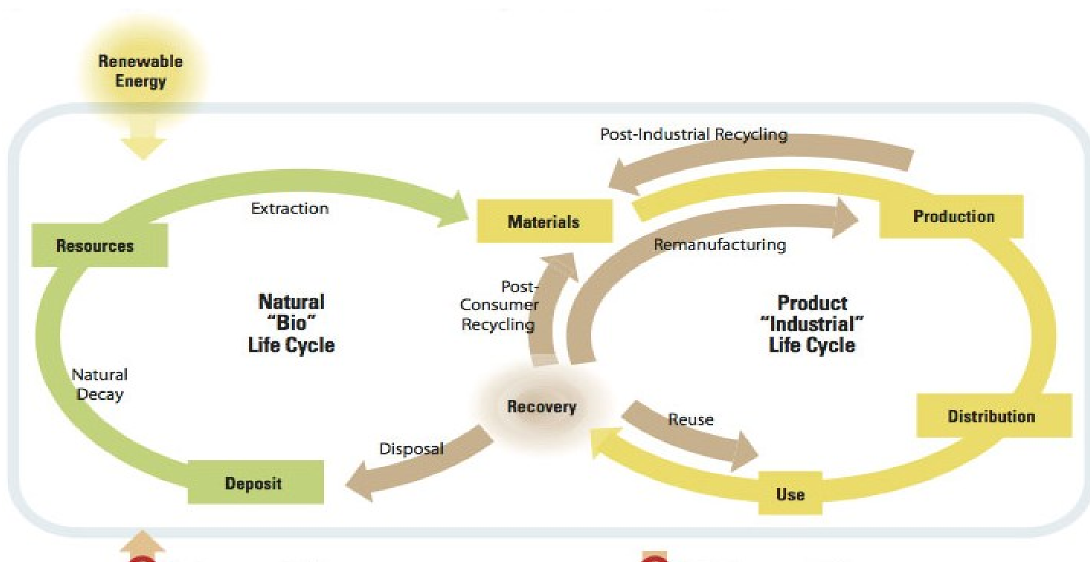

Figure 1. Life cycle of product

Any environmental, economic or social assessment method for products has to take into account the full life cycle from the raw material selection, to the end of life of the product. In other words, a systems approach has to be taken. Only in this way can trade-offs be recognized. Life cycle thinking is the prerequisite of any sound sustainability assessment. It does not make sense to improve (environmentally, economically, or socially) one part of the system in one step of the life cycle, or in one environmental compartment, if this improvement has negative consequences for other parts of the system which may be greater than the advantages achieved [16].

In the life cycle of a product, PD takes place before production and it occurs once for each new product. It is well known however that only 5–7% of the entire product cost is attributable to early design, the decisions made during this stage lock in 70–80% of the total product cost [17]. Correspondingly, we can hypothesize the same to be the case for environmental impacts [11, 12]. "Based on the estimation from the EU report, 80-90% of all product-related environmental impacts are determined during the design phase of a product." [5]. This means that product sustainability is largely specified during the early design stage. Therefore, PD is one of the most important stages influencing global sustainability. In particular, early design decisions can have a major impact on sustainability. These decisions not only relate to material and manufacturing choices but have far-reaching effects on the product's entire life cycle. Therefore, considering downstream life cycle data in the PD process is essential to achieving true sustainable PD [11].

2.3. Sustainable PD (Tools and Methods)

Taking the life cycle approach to PD requires conducting functionality analyses at the early concept development phase to know how the decisions that are made in PD can ultimately affect the efficiencies of the product across its life. Sustainable PD considers life cycle environmental features of the product during development.

Much research has been done on how companies can integrate environmental criteria into the product design and development stages. A significant number of methods and tools have been developed in order to provide relevant information for engineer designers and product developers about the environmental performance of the product. Although new methods and tools are constantly introduced, it can be presumed that they first arose during the 1990s with the expansion of the design for environment and eco- design concepts [18]. The use of tools is frequently mentioned in literature as an important part of the sustainable PD approach and to provide significant support for the integration of environmental aspects into PD [19, 20, 21, 22, 23]. The term "tool" and "method" in this context are defined in a broad sense as any type of systematic aid to integrate TBL aspects into the product design and development. The tools and methods have been proposed in the literature can range from general frameworks and recommendations to more detailed and complicated environmental assessment tools [18]. They can be categorized in two main categories: guidelines and analytical tools. Focus is given to the tools and methods that are developed and can be employed already during the product development and design process in order to consider the sustainability aspects during those stages. Therefore, a compilation of well-known and more applicable tools, that are available today for integrating environmental aspects into PD, is selected and will be described in the next sections, although for barriers and limitations we attempted to consider all of the tools and methods in the literature.

2.3.1. Guidelines

This category includes all type of methods and tools that provide guidance and generic recommendations on what aspects to consider during product design and development in order to minimize the environmental burdens that can appear during the life cycle of the product. In this category there are several methods and tools, as described in what follows.

In Design for Environment, a guide to sustainable PD, Fiksel [2] defines seven basic principles for companies that want to make PD sustainable as follows: Embed life-cycle thinking into the PD process, Evaluate the resource efficiency and effectiveness of the overall system, Select appropriate metrics to represent product life-cycle performance, Maintain and apply a portfolio of systematic design strategies, Use analysis methods to evaluate design performance and trade-offs, Provide software capabilities to facilitate the application of DFE practices, Seek inspiration from nature for the design of products and systems. It is one of the first guidelines and has been employed in different researches.

Simon et al [24] introduce ARPI (Analyse, Report, Prioritize, Improve), as a four-stage framework for implementing eco design. Firstly an environmental assessment from a life cycle viewpoint is performed. Then the result of analyses is communicated to the company and the feedback is collected. Thirdly the feedback and environmental issues are prioritized and in the last stage improvements are suggested and implemented. ARPI is just a guideline and does not provide methods for analyse, report, prioritize and improve tasks. The method for each step should be selected by the company.

Maxwell and Vorst [9] present sustainable products and/or services development (SPSD). SPSD is a framework for implementing sustainable product and/or service development throughout the entire lifecycle of a product and/or service. One of the important goals of this method is to reduce environmental effects by using services instead of product in terms of reducing the volume of products manufactured while maintaining or increasing profits for the company through service provision. This method could be improved when is combined with an analytical method such as life cycle costing to do more analyses of using services.

Luttropp and Lagerstedt [25] describe "Ten golden rules", which encompass ten general guidelines based on best practice rules which pick up on the key issues necessary when attempting and teaching eco-design. Ten guidelines are: hazardous, housekeeping, weight, energy, upgrade, lifetime, protect, information, mix, structure. The guidelines are intended to be applied early during the goal and specifications stage of the PD process. The Ten Golden Rules are generic and are not intended for direct use in design work. Thus, they need to be customized for each cases.

Byggeth et al [12] developed a method for sustainable PD (MSPD) by defining sustainable product analyses (SPA) modules which include strategic guiding questions to identify potentially critical activities during the life cycle. SPA modules are used at the end of each phases of PD and contain:

Product function, Product design, Material type, Production processes and Purchase. It considers the life cycle of product but it cannot support making trade-off during the PD process.

Ljungberg [26] presented a guideline for sustainable PD with special regard to material, design and ecology. The guideline includes a description of materials selection and models for design based on a sustainable society. The selection of material is to optimize a product mainly with regards to: Production methods, Function and structural demands, Market or user demands, Design, Price, Environmental impact and Lifetime. This tool just considers the material and does not have life cycle thinking.

Ulrich and Eppinger [27] define seven steps in terms of considering environmental aspects of product in PD phases as follows: set DFE agenda, identify potential environmental impact, select DFE guidelines, apply DFE guidelines to initial design, assess environmental impact, refine design, reflect on DFE process and results.

Mulder [28] presented The Lifecycle Design Strategies, or LiDS Wheel. These strategies are clustered into eight categories that each contains a number of basic rules that are as follows: New Concept Development (Dematerialisation, Shared use of the product, Integration of functions, Functional optimization of product (components)), Selection of low-impact materials (Non-hazardous materials, Non-exhaustable materials, Low energy content materials, Recycled materials, Recyclable materials), Reduction of material (Reduction in weight, Reduction in (transport) volume), Optimization of production techniques (Alternative production techniques, Fewer production processes, Low/clean energy consumption, Low generation of waste, Few/clean production consumables), Efficient distribution system (Less/clean packaging, Efficient transport mode, Efficient logistics), Reduction of the environmental impact in the user stage (Low energy consumption, Clean energy source, Few consumables needed during use, Clean consumables during use, No energy/auxiliary material use), Optimization of initial life-time (Reliability and durability, Easy maintenance and repair, Modular product structure, Classic design, User taking care of product), Optimization of end-of-life system (Reuse of product, Remanufacturing/refurbishing, Recycling of materials, Clean incineration).

Such tools provide general guidance to the designers of the product, acting in some cases as rules, monitoring or exclusion lists or recipes for environmentally friendly design. They summarize key environmental aspects which should be considered during decision making processes. They often act as a checklist to ensure that the user is aware of the main issues during the design.

2.3.2. Analytical tools

Analytical tools provide detailed and/or systematic analysis at specific stages of either the product development process or lifecycle in order to have an overview of the environmental performance of the product as well as an indication of the properties that need to be improved [2]. They help the designer to identify specific areas and activities related to the product that need to be optimized. These methods are for different purposes such as: screening to narrow design choices among a set of alternatives, performance assessment to estimate the expected performance of designs, Trade-off analysis to compare the expected cost and performance of several alternative design [29]. Some well-known tools of this category are discussed as follows.

The most common technique for evaluating environmental impacts of a product probably is the life cycle assessment (LCA) methodology [30] that has been practiced by industry worldwide for over three decades [31]. The methodology involves four major steps: Determine the goals and scope of the LCA; Compile an inventory of energy and material inputs and environmental outputs across all relevant life cycle stages; Evaluate relevant environmental impacts associated with the life-cycle inputs and releases; Interpret the results to lead to a more informed decision. These steps should be regarded for all PLC stages. Its accuracy and wide scope requires an enormous amount of data for completion. This makes LCA very complex and time consuming. Because of this reason, researchers developed simplified life cycle assessments to reduce the amount of data required [32, 33]. In the Simplified life cycle assessment (SLCA) the methodology is the same as LCA, but some parameters such as inventory data or certain impacts are not investigate during the implementation and evaluation process [34]. The SLCA and LCA methods can only indicate the specific life cycle stage where the majority of the impact is occurring. The engineers must then come back to their usual resources and design process, in order to generate alternate solutions.

Byggeth [35] propose MET matrix, a simple to use environmental analysis method, is applied to map the different environmental impacts of a product during its life cycle and then identify the most significant ones. It can be used early in the product planning and development stage. It provides a general view of the inputs and outputs of each phase of the product life cycle focuses on three aspects of a product: materials, energy and toxicity. MET identifies the main environmental aspects and possible environmental improvement options. The data and results of the tool can be both qualitative and quantitative (when weighting factors are applied to the impact categories).

Yarwood and Eagan [36] propose the Design for environment matrix (DfE Matrix) as a semi-quantitative assessment tool to evaluate different aspects of the product design in relation to their environmental performance. The tool has two modules: a matrix and a list of 100 questions. The matrix is filled with the individual scores. The scores are obtained by answering the questions for each of the life cycle stage (every answer can obtain 0-5 points). The scores can be used to identify areas and aspects that need to be considered and optimized by the designers of the product. The DFE matrix could be used by the designers to provide them rough information about aspects and parameters of the product that might need improvements.

Masui et al [10] introduce the quality function deployment for environment (QFDE) as one of the few methods that link the stakeholder requirements to the environmental performance of product. They define four phases as: deployment of VOC to Engineering Metrics (EM), deployment of EM items to Components of Product, estimate the effect of design changes on the engineering metrics, and the last phase is translating the effect of design changes on EM into environmental quality requirements. QFDE identifies the relationships between different requirements and can help design engineers select the most effective design changes' plan. The various requirements are weighted based on their importance and an evaluation process is then performed in order to rate the relationship between the requirement and the environmental parameter [37]. This tool cannot support making trade-offs.

Hastings [38] defines Life Cycle Costing (LCC) as the analysis of the cost of acquiring, introducing, operating, maintaining and disposing of equipment which include all internal costs plus external costs incurred throughout the entire life cycle of a product, process or activity. It is "cradle to grave" cost analysis. In LCC the costs related to acquisition, operation and through life support are brought together in a spreadsheet or in a similar purpose built system, and the total costs across the life cycle are calculated in the form of the Net Present Value (NPV) and the Equivalent Annual Cost (EAC). It can be improved by combining with other tools such as LCA.

The Product Sustainability Index (ProdSI) is a common qualitative assessment product sustainability evaluation method that comes from Fliksel et al [6]. The ProdSI evaluates sustainability base on TBL (economic, environment and society) in five levels with specific clusters and sub clusters in each sub-index of economic, environment and society. Zhang et al [39] present a new methodology to evaluate five-level Product Sustainability Index (ProdSI) based on a set of product sustainability metrics. They define different metrics for each of the sub clusters. Weights are assigned to all sub-indexes, clusters and sub clusters base on the importance of each.

Some of the tools presented above contain only an evaluation process in order for the impacts to be defined and in some cases quantified, while others provide prioritization and weighting of the identified impacts in order for the user to screen the most important issues that need to be considered. There have been efforts to combine different tools in this category such as LCC with LCA [40] or multi criteria decision making with LCA [41]. Comparisons of different product concepts, alternatives and improvement options are also offered by some of the tools listed in this category.

May et al [5] have criticized environmental tools and methods for having a rather vague connection to the PD process. Also relevant tools are not available for product design phase and existent tools are not adapted to designers' needs, therefore sustainability could not be integrated during early design in most of the cases [5]. In the next section limitation and barriers of current tools and methods are assessed.

2.3.3. Limitation of current tools and methods

Although a vast number of tools have been developed, there still appear to be barriers to their adoption in use. We can summarize list of reasons for poor industrial use of tools as follows:

Weak support of trade-offs: In the PD, there are many elements to consider and mostly, trade-offs are necessary when choices have to be made between different alternatives. In order to support different trade-off situations, the tool should include criteria in a sustainability perspective and other important aspects e.g. cost, quality [35]. Byggeth et al [35] have analyzed fifteen different eco-design tools and highlighted the significance of a new eco-design tool having an evaluation method which provides support in trade-off situations.

Difficult to learn, understand and use: Environmental impacts are one of the many other constraints designers must meet when developing a product. They have very little time to dedicate to them [25, 2]. Some of the tools such as LCA require high training and data gathering to implement. Although the objective with such tools is to assist product designers and increase the consideration of environmental aspects during the product design process, increased data and time requirements can be considered as significant obstacles for those objectives to be fulfilled, and for the tools to be actually used [42, 43, 9]. Also the information attained is often too vague and general, or too complex and abstract to immediately highlight possible solutions. On the other hand tools such as, The Ten Golden

Rules showed guidance consisting mainly of general statements broad enough to cover a range of issues, such as “Use the lowest energy-consuming components available”, without any additional information to back it up. Therefore it is of little direct use to the designer [35, 2].

Weak connection with PD process: the linkage between eco-design tools and PD process is weak or completely missing [44, 9]. Most of the eco design tools and methods activities act as a separate stream [12]; this can marginalize efforts resulting in them and reduce efficiency of the methods. A method or tool should work and promote within PD process; it cannot stand as separate activity [45, 46]. It has been highlighted that researchers in this field need to investigate PD processes to know how environmental concerns can be translated into product specifications [47, 42]. Sometimes the problem is in company with unstructured PD process.

Lack of life cycle thinking: some tools and methods consider one or two stages of life cycle. As mentioned before it has a great risk. The best example is design for X tools for each specific phase of the product life cycle, like design for manufacture, design for assembly, design for disassembly, design for reuse, design for recycle etc. These tools are developed in isolation, and there is very little or no integration of these tools into the design process. During PD there is a need to consider the whole lifecycle rather than a single phase of a product in order to ensure that detrimental environmental effects are reduced and not just relocated to other areas of the products life [48].

Lack of holistic method: To have a sustainable new product we need guidelines and checklists to consider different drivers of sustainability in each of the phases of a PD process. In addition, we need to analyze sustainability of the proposals in different phases of PD. Also we should have trade off tools to select between different alternatives. Although there have been some efforts to provide a more holistic approach [11], qualitative tools like guidelines are used in the initial phases, and quantitative tools like LCA, which require great amount of data, time and effort, are used in the later stages of design. There is no communication between these tools or results of them. Lofthouse [49] highlighted the importance of developing holistic tool for industrial designers, recognizing that a combination of guidance, checklist, education and information, along with well-considered content, appropriate presentation and easy access, are critical to success.

Lack of communication: Tools and methods should promote multifunctional teamwork. In current tools there is no clear indication, on who would be the most suitable user of tool. Environmental experts have all necessary knowledge to do the assessments and translate the results, while engineers are more aware of the product specifications [22]. Although in the literature emphasize the importance of multifunctional teamwork and the exchange of information [50, 51, 42], the nature of the implementation process of some tools and methods sometimes makes it impossible for both sides to be able to use the tools. In addition, the outcome of such tools can be difficult for everyone to understand and correctly communicate to the rest of designers or company in general. Summary of current limitations is illustrated by the black boxes in Table 1.

Table 1. Limitations of current tools and methods.

Shortcomings / **Tools and Methods**	Weak support of trade offs	Difficult to learn, understand and use	Weak connection with PD process	Lack of life cycle thinking	Lack of holistic method	Lack of communication
DFE (Fiksel 2009)		■	■		■	
ARPI		■			■	■
SPSD	■					■
Ten Golden Rules	■	■	■		■	
MSPD	■					■
Guidline (Ljungberg)	■			■		■
DFE (Ulrich and Eppinger)	■				■	
LiDS Wheel	■		■		■	■
LCA		■	■			
SLCA	■	■	■			
MET matrix			■		■	■
DfE Matrix	■				■	
QFDE	■			■		■
LCC		■	■		■	
ProdSI		■	■			■

2.4. Solutions

Based on the presented barriers and limitations, in this section we propose two solutions to address current shortcomings. They can be explained as new methods for sustainable PD that can cover the requirements of designers in the PD process and that integrate sustainability.

2.4.1. Developing a model to support trade-offs in sustainable PD

In sustainable PD, besides the need of making trade-offs between different environmental issues, sometimes we need to make trade-off between environmental issues and other features of new products such as cost, quality etc. Developing a new method that could model different features and make this trade-off could be investigated. The new model is not just making an evaluation and comparing different proposals but it models different specifications of a new proposal to make trade-offs among sustainability and other customer requirements such as cost, quality etc. A scoring model could be defined to model sustainability, quality and cost in order to find the optimum level of their combination thereof. By using this model, designers are capable of prioritizing different concepts in regard to select the best one. To make such a scoring model three groups of customer requirements are defined: cost, quality and sustainability. For each group a QFD matrix is considered that deploys each group of customer requirements (CR) to design specifications (DS). Design specifications are the same for all the groups of CR's.

For each of the QFD matrices we have the following parameters:

- CRit = Customer Requirements for tth matrix, i= 1…m, t= 1,2,3.
- DSj = Design Specifications, j= 1…n.
- Wit = Weight of importance for ith CRi of tth matrix, t= 1,2,3.
- Rijt = The strength of the impact of the jth DS towards fulfilling the ith CR for tth matrix, t= 1,2,3.
- Xj = decision variable for attainment for the jth DS,

All Xj should be normalized to be in a same range. Each of them is defined as direct impact '+' (more is better) or indirect impact '−' (less is better). All Xj(s) are scaled to [0,1] and Xj = 1 when the target is reached. To do this scaling following formulas are used: ($\mathrm{L(X_j)}\ \mathit{Lower}\ \mathrm{X_j}, \mathrm{U(X_j)}\ \mathit{Upper}\ \mathrm{X_j}$)

For '+', $\mathrm{X'_j} = \frac{\mathrm{X_j - L(X_j)}}{\mathrm{U(X_j) - L(X_j)}}$ (1)

For '−', $\mathrm{X'_j} = \frac{\mathrm{U(X_j) - X_j}}{\mathrm{U(X_j) - L(X_j)}}$ (2)

For the quality matrix, it is the same as the traditional QFD, but for cost and environment, we define specific customer requirements which lead to specific QFDs (Green QFD and Cost QFD). LiDS Wheel strategies considers the whole lifecycle and indicates significant requirements for each of the steps in the lifecycle. The strategies follow the lifecycle of the product from resource acquisition to waste disposal, therefore it is used as customer requirements in the Green QFD matrix [28]. For cost requirements, we consider the cost items for different lifecycle stages like GQFD-II [52]. The five major CR(s) for the cost matrix are: material cost, production cost, transportation cost, use cost and end of life cost. We can model each QFD matrix as:

$$\text{Max } Z = \sum_{i=1}^{m} w_i y_i \quad (3)$$

$$\text{S.T: } y_i = \sum_{j=1}^{n} R_{ij} X'_j, \; i=1,2,\ldots,m \quad (4)$$

$$X'_j = f_j(X'_1, X'_2, \ldots, X'_n) \leq 1, j = 1,2, \ldots, n \quad (5)$$

There might be a correlation between the DS(s), and this can be defined by a scale of 0, ±1, ±3, ±9, 18. 18 is just for the correlation between the same DS [53]. Tij denotes the degree of dependence of the ith DS on the jth DS. No dependence Tij=0. Tij should be scale to Tij $\in [-1,1]$ and Tii =1. The correlation between a pair of DS may not necessarily be bidirectional nor equal in strength. In a normalized correlation matrix T, the element Tij can be interpreted as the incremental change of the degree of attainment for the jth DS when the ith DS is increased by one unit [53]. Therefore, Tij quantitatively set the amount of change in DSi as a result of a unit increase (or decrease) in DSj. Such relationships are initially assumed to be linear.

The final X'_j will be calculated as follows:

hj = the planned attainment for the jth DS,

$$X'_j = h_j + \sum_{k \neq j} T_{kj} h_j = \sum_{k=1}^{n} T_{kj} h_j. \quad (6)$$

S.t:

$$0 \leq h_j + \sum_{k \neq j} T_{kj} h_j \leq 1, \; j = 1,2, \ldots, n. \quad (7)$$

The Wi can be found through the application of the fuzzy analytical hierarchy process (FAHP). For FAHP, we utilize the method which was originally introduced by Ertuğrul [54] to quantify the importance of each customer requirements based on customer opinion.

In this step we need to model the belief and usefulness of customers for each group of CR(s). For this reason we employ MAUT. We specify the utility function for each group of customer requirements (sustainability, quality and cost) in a constant absolute risk aversion (CARA) set-up as follows:

Ui(Zi) = bi + ai × exp(-ciZi). (8)

Zi is obtained from QFD matrices and the range of the Z is calculated by putting the maximum and minimum amount of DSj(s) in it. This function shows the utility of producers for each group of the customer requirements. The coefficient ci reflects the degree of risk aversion. ai and bi are for normalization and are calculated such that Ui(Zi) is scaled from 0 to 1. Up until now, we have three utility functions for environment, cost, and quality that are calculated based on the output of QFD objective functions (Zi). The next step is to evaluate total utility of the stakeholders. The utility U(x) of combination of outcomes of three goals (Minimum cost, maximum quality and maximum sustainability) can be obtained from the solution to the following equation [55]:

$$U(x) = \frac{1}{K}\{\prod_{i=1}^{n}[Kk_i U_i(x_i) + 1] - 1\} \quad (9)$$

K is a scaling constant that is a solution to: -1 ≤ K≤ 0

$$1 + K = \prod_{i=1}^{n}[Kk_i + 1] \quad (10)$$

ki is the utility if attribute i is at its best value, and all attributes except i are at their respective worst values. Different types of questions are assessing the ki's [56]. We now have three group of customer requirements which are combined into one objective function by MAUT. Once designers define CR(s), DS(s) and weights for different designs, they can easily calculate the final value for total utility and by changing the importance of each group of CR(s) (sustainability, quality and cost) they can make trade-offs among them.

A simple case study revised from what was given by [57] is presented to show how the proposed model works. A pencil-manufacturing firm is going to develop a new product. The example is extended with some modifications.

The design specifications are shown in Table 2.

Table 2. Design specifications

No	Design specifications	Xi,min	Xi,max	Unit [1]
DS1	Length	10	20	CM
DS2	time between sharpening	3	6	page
DS3	lead dust generated	1	4	g
DS4	Hexagonality	0	100	percentage
DS5	erasure residue	0.005	0.03	mg/cm^2

The correlation between design specifications are obtained from the example which is shown in Table 3. These determine Tkj(s) in our model.

From a market survey, four major CR's for quality have been identified [57]:

CRQ1. Easy to handle, CRQ2 Does not smear, CRQ3. Point lasts (CR3), and CRQ4. Does not roll.

The QFD matrix for these CR(s) is shown in Table 4.

Table 3. Normalize Correlation between DS (Tij) [53]

	DS1	DS2	DS3	DS4	DS5
DS1	1	0	0	0	0
DS2	0	1	0.167	0	0.167
DS3	0	0.167	1	0	0.5
DS4	0	0	0	1	0
DS5	0	0.167	0.5	0	1

Table 4. Normalize QFD for quality

Normalize QFD for quality (Lyman's normalization)							
	Wight [1,2]		DS1	DS2	DS3	DS4	DS5
Y11	0.17	CRQ1	0.25	0	0	0.75	0
Y12	0.25	CRQ2	0	0.189189	0.405405	0	0.405405
Y13	0.41	CRQ3	0.022026432	0.185022	0.396476	0	0.396476
Y14	0.17	CRQ4	0.1	0	0	0.9	0

Weights of importance for each CR are calculated based on FAHP method [54].

For cost customer requirements as mentioned before, we consider the same costs as the GQFD II, five CR's which cover the life cycle of the product. Therefore the CR's for cost are: CRC1. Material cost, CRC2. Production cost, CRC3. Transportation cost, CRC4. Use cost, and CRC5. End of life cost.

The QFD matrix for these CR(s) is shown in Table 5.

Table 5. Normalize QFD for cost

normalize QFD for cost (Lyman's normalization)							
	Weight		DS1	DS2	DS3	DS4	DS5
Y21	0.21	CRC1	0.052631579	0.252632	0.347368	0	0.347368
Y22	0.21	CRC2	0.272727273	0.3	0.163636	0.090909	0.172727
Y23	0.21	CRC3	1	0	0	0	0
Y24	0.17	CRC4	0	0.126761	0.401408	0.070423	0.401408
Y25	0.2	CRC5	0.652173913	0.217391	0.065217	0	0.065217

As mentioned before for green CR's we consider the LiDS Wheel which has eight categories that each contains a number of basic rules. In this example we just consider the first level of strategies. It considers the whole lifecycle and indicates significant requirements for each of the steps in the lifecycle. Therefore, the CR's for environment are: CRE1. New Concept Development, CRE2.Selection of low-impact materials, CRE3. Reduction of material, CRE4. Optimization of production techniques, CRE5. Efficient distribution system, CRE6. Reduction of the environmental impact in the user stage, CRE7. Optimization of initial life-time, CRE8. Optimization of end-of-life system.

The QFD matrix for environment CR's is shown in Table 6.

Table 6. Normalize QFD for Environment.

Normalize QFD for Environment (Lyman's normalization)							
	Weight		DS1	DS2	DS3	DS4	DS5
Y31	0.08	CRE1	0	0.189189	0.405405	0	0.405405
Y32	0.14	CRE2	0	0.136364	0.443182	0	0.420455
Y33	0.2	CRE3	1	0	0	0	0
Y34	0.1	CRE4	0	0.136364	0.409091	0	0.454545
Y35	0.08	CRE5	1	0	0	0	0
Y36	0.18	CRE6	0	0.266667	0.366667	0	0.366667
Y37	0.15	CRE7	0.056818182	0.528409	0.210227	0	0.204545
Y38	0.07	CRE8	0	0.136364	0.420455	0	0.443182

Based on expert answers to lottery questions, C1, C2 and C3 are calculated as 0.2, 0.18 and 0.26 respectively which shows degree of risk aversion for each attribute. ki are calculated in the same way based on expert opinions: k1=0.6, k2=0.52 and k3=0.4, therefore K=-0.7855.

Now for three concepts with the following values for design specifications we can calculate the total utility and select the best one. Table 7 shows utility of quality, cost and sustainability of three concepts besides the total utility for each. Therefore, designers can compare these three concepts based on different issues (cost, Quality and sustainability) and select the best one.

Table 7. Final Utility for three different concepts

No	Design specifications	Concept 1	Concept 2	Concept 3
DS1	length	10	12	10
DS2	time between sharpening	5.422	4.5	4.32
DS3	lead dust generated	2.269	3	1.5
DS4	hexagonality	100	80	20
DS5	erasure residue	0.015	0.02	0.01
	U(Quality)	0.937	0.671	0.842
	U(Cost)	0.387	0.518	0.352
	U(Sustainability)	0.737	0.538	0.834
	Total Utility	**0.81**	**0.70**	**0.76**

Based on the results first concept has the maximum utility and should be selected, although the maximum sustainability is for the third concept or the maximum cost is for the second one.

2.4.2. Defining a systemic holistic method that considers different features of sustainability and product life cycle in appropriate and related phases of PD.

There are various works on tools and methods, but little is said on how to combine and integrate these within the design process. Also there is no comprehensive method that could be useful for the whole lifecycle of a product in various stages of its PD for both synthesis and analysis [58].

The required method consists of different kinds of guidelines and analytical methods that are integrated. The question on how to combine the results of different tools, or even to integrate different tools, is open for study [43]. In the new method, specific guidelines and checklists would be defined for different phases of the PD process that begin from the first phase and continue until the end of the process. A prioritization matrix would be applied to evaluate and prioritize different solutions, and also tools for making trade offs would be considered. One of the goals is to integrate different applicable tools with each other in such a way that the output of one could be used as an input of the other. Guidelines should be defined based on the standard PD process and the method would support the information regarding when and how the different environmental features should be considered in the PD process in order to increase the connection between the new method and the PD process. Finally the holistic method should be easy to use and understand.

2.5. Conclusions

In this article we highlighted the importance of sustainable PD and categorized different well-known existing tools and methods for sustainable PD into two major groups. The lack of current tools and methods is assessed and categorized into six groups. Finally two solutions are proposed to meet current barriers and limitations which one of them is followed and a scoring model introduced as a new tool for sustainable product development. For future works the second solution can be followed and also the scoring model which proposed can be extended to an optimization model. An optimization model could be proposed to model sustainability, quality and cost in the PD process in order to find the optimum level of their combination.

3. Chapter 3: A new model of sustainable product development process for making trade-offs

This article, entitled "A new model of sustainable product development process for making trade-offs" was accepted for publication in the *International Journal of Advanced Manufacturing Technology* [59]. The titles, figures, tables, algorithms and mathematical formulations have been revised to the keep the coherence through the thesis.

Abstract

The decisions made during product development (PD) lock in 70–80% of total product cost, and the quality of the product is also largely fixed. Therefore, these decisions have a great influence on product life cycle cost, quality and sustainability. To improve such decisions, designers need to make high level trade-offs among various criteria to see their effects. Therefore, developing a model to support trade-offs for sustainable product development is a significant concern for designers. This research attempts to consider sustainability, quality and cost simultaneously to make trade-offs between environmental issues and other customer requirements to select the best design specifications on their basis. Sustainability is considered as a customer requirement, which then is translated into design specifications. In this study, sustainable design is treated as an optimization problem to maximize value-added activities while minimizing environmental effects. Multi attribute utility theory is utilized in order to formulate combination of the customer's opinions and make a trade-off between different groups of customer requirements in the final model. An optimization model is then defined to model sustainability, quality and cost in the product development process in order to find the optimum level of their combination thereof. By using this model, designers need not select between different solutions since they can find the optimal solution. A case study is illustrated and the results are discussed.

3.1. Introduction

The environment has become one of the most significant issues for manufacturers. Companies, recognize that besides profits, there are other elements in the long-term success that are important to consider [9], issues such as the future of the planet and the future of generations to come. In order to best address these issues, they must be taken into account during product development (PD). Early decisions in PD can have a significant impact on the sustainability of product realization since by the end of the PD process, the sustainability attributes of the product are largely fixed [11]. This could be the same for other aspects of new design as the decisions made during PD lock in 70–80% of the total product cost and the quality of the product is also fixed during the PD process [11, 12].

Although a vast number of tools have been developed to make PD sustainable [60], there still appear to be barriers to their adoption in use. One of the barriers in current tools and methods for sustainable PD is weak support of trade-offs. In PD, there are many elements to consider and trade-offs are necessary when choices have to be made between different alternatives. The tool should be capable of making trade-offs between criteria with a sustainability perspective and other important aspects e.g.

cost and quality [35]. Most of the current tools for sustainable PD can only compare different concepts and cannot make trade-offs to find the optimal concept and check the effect of sustainability issues on the other features of the product.

Sustainability aspects should be considered as customer requirements (CR), which will then translate into design specifications. Design specifications (DS), which are also known as "engineering characteristics" (EC) or "technical attributes" (TA), are a translation of the voice of the customer into the technical response of the engineer and they must all have units of measure and must be measurable [61]. The DSs are defined and improved to meet customer requirements and maximize their satisfaction. This is usually done through the implementation of quality function deployment, which, through increased product complexity, market competition and limited resource, requires more accurate and optimal solutions. Most of the trade-offs between sustainability and other elements take place in the process of defining specifications and their targets. By finalizing the design specifications, the sustainability, cost and quality of the product are largely finalized. Therefore, this is a critical concern in this research.

The nature of the PD process is vague with a high degree of uncertainty. Uncertainty continues until the prototype is produced, after which it is greatly reduced though not eliminated, and is the main cause of significant rework during the PD process. When designers search for values for design specifications, they begin with imprecise ones. They often begin by defining minimum and maximum values for each design specification. It can be helpful if a model illustrates final satisfaction of customer requirements for any specific group of design specification values, and also can calculate initial optimum values of DSs to start with in order to have maximum CR satisfaction. It reduces reworks during the PD process as well.

In this study environmental design is treated as an optimization problem to maximize value-added activities while minimizing resource consumption and waste dispersion activities.

A new approach is proposed to consider all of the features simultaneously to make trade-offs between environmental issues and other customer requirements and to find initial optimum values for design specifications on their basis, so that possible trade-offs can be diagnosed early in the design process, when the cost is low and changes in the design are easily made [62]. Numerical experiments are proposed to check computational efficiency and verify the model. The output is initial optimum (let's not call it optimum here) values for design specifications which maximize customer satisfaction by considering different constraints, such as budget. These values are considered as the target values for DSs.

The next section provides a literature review; section 3 presents the methodology and optimization model. Section 4 describes the case study, and finally results and conclusions are discussed in Section 5 and 6 respectively.

3.2. Literature review

Much research has been done on how companies can integrate environmental criteria into the product design and development stages. A significant number of methods and tools have been developed in order to provide relevant information for engineer designers and product developers about the environmental performance of the product. Although new methods and tools are constantly introduced, it can be presumed that they first arose during the 1990s with the expansion of the design for environment and eco- design concepts [60]. The use of tools is frequently mentioned in literature as an important part of the sustainable PD approach and to provide significant support for the integration of environmental aspects into PD [19, 20, 21, 22, 23]. The term "tool" and "method" in this context are defined in a broad sense as any type of systematic aid to integrate TBL (Triple Bottom Line) aspects into the product design and development. The tools and methods have been proposed in the literature can range from general frameworks and recommendations to more detailed and complicated environmental assessment tools [60]. Although a vast number of tools have been developed, there still appear to be barriers to their adoption in use. We can summarize list of reasons for poor industrial use of tools as follows:

Weak support of trade-offs: In the PD, there are many elements to consider and mostly, trade-offs are necessary when choices have to be made between different alternatives. In order to support different trade-off situations, the tool should include criteria in a sustainability perspective and other important aspects e.g. cost, quality [35]. Byggeth et al (2006) have analyzed fifteen different eco-design tools and highlighted the significance of a new eco-design tool having an evaluation method which provides support in trade-off situations.

Weak connection with PD process: the linkage between eco-design tools and PD process is weak or completely missing [44, 9]. Most of the eco design tools and methods activities act as a separate stream [12]; this can marginalize efforts resulting in them and reduce efficiency of the methods. A method or tool should work and promote within PD process; it cannot stand as separate activity [45, 46]. It has been highlighted that researchers in this field need to investigate PD processes to know how environmental concerns can be translated into product specifications [47, 42].

Lack of life cycle thinking: some tools and methods consider one or two stages of life cycle. As mentioned before it has a great risk. The best example is design for X tools for each specific phase of the product life cycle, like design for manufacture, design for assembly, design for disassembly, design for recycle etc. During PD there is a need to consider the whole lifecycle rather than a single phase of a product in order to ensure that detrimental environmental effects are reduced and not just relocated to other areas of the products life [48].

Lack of holistic method: To have a sustainable new product we need guidelines and checklists to consider different drivers of sustainability in each of the phases of a PD process. In addition, we need to analyze sustainability of the proposals in different phases of PD. Also we should have trade off tools to select between different alternatives. Although there have been some efforts to provide a more holistic approach [11], qualitative tools like guidelines are used in the initial phases, and quantitative tools like LCA, which require great amount of data, time and effort, are used in the later stages of design. There is no communication between these tools or results of them. Lofthouse (2006) highlighted the importance of developing holistic tool for industrial designers, recognizing that a combination of guidance, checklist, education and information, along with well-considered content, appropriate presentation and easy access, are critical to success [49].

The model introduced here supports the making of high-level trade-offs during the PD process among sustainability, cost and quality, and within different criteria in each group. It is completely integrated in the PD process, as QFD is an inseparable part of PD process. The cost and sustainability issues are considered as a new group of customer requirements and all customer requirements are considered for the life cycle of the product.

QFD is a planning and problem-solving tool that is well known and widely used for translating customer requirements (CRs) into design specifications (DSs) of a product. For using QFD in design process although a vast number of research has been done [63, 64, 65, 66, 67, 10, 68], but only a limited number of researchers have modeled output of the QFD matrices to optimize a design [69]. To the best of our knowledge, not much research is done on quantitative models for QFD, especially optimizing customer requirements. The idea is more about quantifying the model but also making trade-offs through the consideration of environmental factors.

Locascio and Thurston (1998) combine the qualitative design information gathered from QFD with quantitative constraints used in design problems to define a multi attribute design optimization problem where the goal is to maximize design efficiency [70]. Rao and Freiheit (1991) use modified game theory to generate Pareto optimal solutions (where improving one goal will cause at least one other to worsen) to the design of a machine tool gear train [64]. Dawson and Askin (1999) define a design problem that allows correlated engineer characteristics (ECs), non-linear empirical value functions and non-linear feasibility constraints to optimize [71]. They propose a non-linear mathematical program for determining the optimal engineering specifications during new product development as a function of extracted customer value functions, production costs, engineering development and development time. Fung et al. (2002) created a fuzzy nonlinear optimization model to find optimum technical attributes [53]. Design budget is considered as a constraint in the final model and the relationship between technical attributes is modeled. Karsak (2004) utilized the fuzzy Delphi method to determine the importance of customers' needs and the level of fulfillment of design requirements through a fuzzy multiple objective programming. Tang et al (2002) proposed a model to optimize technical attributes by considering the cost required and the actual planned cost for production. Two types of fuzzy optimization models are discussed and optimum values for DSs are determined. Chen et al (2004) proposed a model to find the optimum target values for engineering characteristics (EC). They have applied fuzzy regression-based mathematical programming to model the relational functions between ECs and CRs, and among ECs. The cost of the PD process is considered as a constraint in the optimization model.

Kahraman et al (2006) proposed a framework based on QFD and fuzzy analytic network process. An optimization model is proposed to determine the importance of the design specifications and is applied in a Turkish Company producing PVC windows and doors. Kwong et al (2007) use QFD to calculate impact values of engineering characteristics (ECs). They applied fuzzy expert system to quantify linguistic parameters in QFD matrix [63].

As we can see in the literature, there is very little research that considers environmental issues in finding the values of the design specifications. The approach here takes previous efforts one step further by considering environmental, cost and quality requirements in three different QFD matrixes and then combines them in one optimization model to find initial optimum design specifications for the maximum utility of stakeholders. Considering three QFD matrices increases accuracy because each criteria of each group of CRs is compared with other criteria of the same group. It is easier to compare as customers are asked to compare between parameters with a same nature, such as cost. Then three groups of CRs are combined. Multi attribute utility theory is employed to model comparison and trade-offs between three groups of CRs; therefore, it goes beyond Pareto optimal and weighted sum solutions. This research looks for how to combine the goals, or Pareto optimal points, such that their overall combination is optimal. Designers and customers can make trade-off between and within each group of CRs. Finally the life cycle of the product is considered to define design specifications.

3.3. Methodology

By deciding on design specifications of one product, the final features of the product will be fixed. One of the most important features for all products in sustainable design is its environmental effect. Therefore, we attempt to consider environmental features when designers are deciding about the DS(s). At the moment, there are many concerns that have influence on the values of the DS(s). The proposed model considers environmental issues along with other concerns during the process of defining values for DS(s). This makes sure the final design has been considered to have less environmental effect, and also could illustrate the effect of reducing the environmental impact on other features such as cost and quality of the product which helps decision makers make better decisions.

The design decision problem is modeled using Quality Function Deployment (QFD), Analytical Hierarchy Process (AHP) and Multi Attribute Utility Theory (MAUT), as described in the following sections.

3.3.1. Quality Function Deployment (QFD)

One of the most critical issues during the design process is to convert customer needs into design specifications; designing products that effectively meet or even surpass customers' expectations is vital to maintain market share [70]. QFD links subjective product goals to the engineering domain quantitatively, identifying the relationships between what the customer wants and what the engineering design team must do to provide it [71]. Comparing two customer requirements from two different groups is not convenient, for example it does not make sense to ask about the importance of the power of an engine (quality requirements) in comparison to clean packaging (environmental requirement). These are two different concepts and are not comparable. Thus, we compare customer requirements within each group, and then consider the importance of three groups of CRs with respect to each other. In this research, we use QFD to transform three groups of customer requirements (cost, quality and environmental issues) into design specifications. From each matrix a function is extracted which shows the total value of the respective group of customer requirements. For each of the QFD matrices we have the following parameters:

- CRit = Customer Requirements for tth matrix, i= 1…m, t= 1,2,3.
- DSj = Design Specifications, j= 1…n.
- Wit = Weight of importance for ith CRi of tth matrix, t= 1,2,3.
- Rijt = The strength of the impact of the jth DS towards fulfilling the ith CR for tth matrix, t= 1,2,3.

The focus here is on environmental requirements when considering the life cycle of the product.

As for the requirements of environmental aspects, there are a large number of environmental considerations in the literature that a designer should consider. The Lifecycle Design Strategies, or LiDS Wheel is among the most known and easy to use tools in eco- design. These strategies are clustered into eight categories that each contains a number of basic rules which follow the lifecycle of the product from resource acquisition to waste disposal. As the LiDS Wheel considers the whole lifecycle and indicates significant requirements for each of the steps in the lifecycle, we use it as customer requirements in Green QFD matrix [28].

For cost requirements, we consider the cost items for different lifecycle stages like GQFD-II [52], for which the five major CR(s) for the cost matrix are: material cost, production cost, transportation cost, use cost and end of life cost.

Rijt indicates the extent to which each customer requirement has been addressed by a design parameter. The intersection of each customer requirement column and design specification row forms a field in the middle of the house. These fields encompass the correlations between the pairs. The normalized Rij, can be interpreted as the contribution of the jth DS towards the complete fulfilment of the ith CR when the target of the jth DS is met.

- Xj = decision variable for attainment for the jth DS, Xj ≤ 1 and Xj = 1 when the target is reached. Xj has minimum that equal to 0.

Each of the DS(s) has a direct or indirect impact which is defined as either '+' (more is better) or '−' (less is better). To decrease the effects of different magnitudes, the technically feasible minimum amount for X is scaled to 0 and the maximum to 1 and all the other amounts should be scaled in between. To do this scaling, the following formulas are used:

For '+', $X'_j = \frac{X_j - L(X_j)}{U(X_j) - L(X_j)}$ (11)

For '−', $X_j' = \frac{U(X_j) - X_j}{U(X_j) - L(X_j)}$ (12)

Where $U(X_j)$ and $L(X_j)$ are upper bound and lower bound of X_j.

We can model the QFD matrices as:

Max Z = $\sum_{i=1}^{m} w_i y_i$ (13)

S.T: $y_i = \sum_{j=1}^{n} R_{ij} X_j'$, i=1,2,…,m (14)

$X_j' = f_j(X_1', X_2', \ldots, X_n') \leq 1, j = 1,2, \ldots, n$ (15)

Engineering specifications may be dependent on one another. They may have a positive or negative affect on others. To define a target for design specifications, it is important to consider these relations and also it is best to realize these dependencies early in the design process [72]. Thus it is important to consider the correlation between DS(s), and this can be defined by a scale of 0, ±1, ±3, ±9, 18. 18 is just for the correlation between the same DS [53]. We define matrix T and each element Tij in T denotes the degree of dependence of the ith DS on the jth DS. No dependence Tij=0. When T is normalized, Tij $\in [-1,1]$ and Tii =1. The correlation between a pair of DS may not necessarily be bidirectional nor equal in strength. Also, in a normalized correlation matrix, the element Tij can be interpreted as the incremental change of the degree of attainment for the jth DS when the ith DS is increased by one unit [53]. Thus, the covariance coefficients (Tij) quantitatively set the amount of change in DSi as a result of a unit increase (or decrease) in DSj. Such relationships are initially assumed to be strictly linear.

The final X_j' will be calculated as follows:

hj = the planned attainment for the jth DS,

$X_j' = h_j + \sum_{k \neq j} T_{kj} h_j = \sum_{k=1}^{n} T_{kj} h_j.$ (16)

S.t:

$0 \leq h_j + \sum_{k \neq j} T_{kj} h_j \leq 1,\ j = 1,2, \ldots, n.$ (17)

The weighting factors (Wi) show the importance of each CR in the Z value of each category of customer requirements. They are calculated based on customer's opinions which are often linguistic and imprecise. Linguistic characterizations differ from numerical ones in that their values are not numbers but are words or phrases. This qualitative data must be translated into numerical scales. In this study the analytical hierarchy process (AHP) is utilized to quantify the importance of each customer requirements based on customer opinion.

3.3.2. Multi Attribute Utility Theory (MAUT)

Design specification optimization is a complex decision-making problem. The complexity comes from a multitude of qualitative and quantitative factors as well as the inner difficulty of making numerous trade-offs among these factors. One analytical approach mostly suggested for solving such complex problems is MAUT. Multiple Attribute Utility Theory (MAUT) is an analytical method for decision-making based on multiple criteria, and was developed by Keeney and Raiffa (1976) [56]. In this study, to model customer's preference we use a risk aversion exponential utility function. The general exponential utility function is defined as $u(x) = -\exp(-x/c)$ where c is a positive constant, and it has the nature of constant absolute risk aversion (CARA). The exponential utility function with CARA property states that the marginal utility of wealth decreases as wealth increases which is the case here, therefore the utility function is concave and is a diminishing marginal utility function [73]. Exponential utility function has extreme convenience for purposes of mathematical modeling. It is also very appropriate as an approximation to anyone's utility function for measuring small to moderate gambles, and for this reason it is widely utilized in applied decision analysis. To formulate a combination of the customer's opinions and make a trade-off between different groups, the MAUT is employed.

We specify the utility function for the three goals of PD (environment, quality and cost) in a constant absolute risk aversion (CARA) set-up. For the absolute risk aversion, parameter c is greater than zero and reflects the degree of risk aversion. Utility function U is exponential and is defined as:

$Ui(Zi) = bi + ai * \exp(-ciZi)$. (18)

Zi is obtained from QFD matrices and the range of the Z is calculated by putting the maximum and minimum amount of DSj(s) in it. This function shows the utility of producers for each group of the customer requirements.

The utility U(x) of combination of outcomes of attributes (quality, cost and environment) can be obtained from the solution to the following equation [55]:

$$U(c) = \frac{1}{K}\{\prod_{i=1}^{n}[Kk_i U_i(x_i) + 1] - 1\} \quad (19)$$

K is a scaling constant which is a solution to: $-1 < K < 0$

$$1 + K = \prod_{i=1}^{n}[Kk_i + 1] \quad (20)$$

Once utility functions for all attributes have been determined, the next step is to fix the weighting value of each ki.

ki is the utility if attribute i is at its best value, and all attributes except i are at their respective worst values. Different types of questions are assessing the ki(s) [56].

3.3.3. Optimization model

We now have three goals which are combined into one objective function by MAUT. Design attributes and variables have allowable ranges defined independently of each other. Constraints represent a dependent relation between attributes and design variables which often reduces these ranges. The final model is presented as follows.

Objective function:

$U(x)\colon total\ utility\ of\ customers\ for\ three\ attributes\colon quality, cost\ and\ environment$

Decision variables:

$h_j\colon the\ planned\ attainment\ for\ jth\ DS$

$X_j\colon attainment\ for\ jth\ DS$

$y_{it}\colon value\ for\ ith\ CR\ of\ tth\ attribute$

$Z_t\colon value\ of\ tth\ attribute$

$U_t(Z_t)\colon utility\ of\ tth\ attribute$

Parameters:

$K\colon scaling\ constant$

$k_t\colon weighting\ for\ each\ attribute$

$a_t, b_t\colon parameters\ to\ scale\ U_t(Z_t)\ from\ 0\ to\ 1$

$c_t\colon degree\ of\ risk\ aversion$

$w_{it}\colon weight\ of\ importance\ for\ the\ ith\ CRi\ of\ tth\ attribute$

$R_{ijt\colon}\ the\ strength\ of\ the\ impact\ of\ the\ jth\ DS\ towards\ fulfilling\ the\ ith\ CR\ for\ tth\ attribute$

$T_{kj}\colon degree\ of\ dependence\ of\ the\ kth\ DS\ on\ the\ jth\ DS$

$Lb_t\colon the\ minimal\ acceptable\ satisfaction\ level\ of\ attribute\ t$

$Ub_t\colon the\ maximal\ acceptable\ satisfaction\ level\ of\ attribute\ t$

$y_{it}^{max}, y_{it}^{min}$: *the minimal and maximal acceptable satisfaction level of CRi (if any of the customer requirements has minimum or maximum, it will show up in the constraints)*

$Max\ U(x) = \frac{1}{K}\{\prod_{t=1}^{T}[Kk_tU_t(Z_t) + 1] - 1\}$ (21)

S.t:

$U_t(Z_t) = b_t + a_t * exp(-c_tZ_t)\ \ \forall\, t = 1,2, \dots, T$ *(22)*

$Z_t = \sum_{i=1}^{m} w_{it}y_{it}\quad \forall\, t = 1,2, \dots, T$ *(23)*

$y_{it} = \sum_{j=1}^{n} R_{ijt}X_j,\quad \forall\, t = 1,2, \dots, T\ and\ i=1,2,\dots,m.$ *(24)*

$X_j = h_j + \sum_{k\neq j} T_{kj}h_j\ \ \forall\, j = 1,2, \dots, n.$ (25)

$0 \leq h_j + \sum_{k\neq j} T_{kj}h_j \leq 1,\ \forall\, j = 1,2, \dots, n.$ (26)

$Lb_t \leq Z_t \leq Ub_t\quad t = 1,2, \dots, T.$ (27)

$y_{it}^{min} \leq y_{it} \leq y_{it}^{max}\ \ \forall\, t = 1,2, \dots, T\ and\ i=1,2,\dots,m.$ *(28)*

$0 \leq h_j \leq 1,\ j = 1,2, \dots, n.$ (29)

For '+', $h_j = \frac{X_j' - L(X_j)}{U(X_j) - L(X_j)}$ (11)

For '−', $h_j = \frac{U(X_j) - X_j'}{U(X_j) - L(X_j)}$ (12)

The output of the model could be considered as initial optimum values to make a concept. We do not expect these values to be the final ones for the end product. As mentioned before, the process of PD is vague and sometimes designers do not have any idea of what could be initial values for DSs to start. This model provides best point to start with, which we call the "initial optimum values". It helps designers easily check and track the effect of any changes in parameters, on the other DSs, and also determine the total utility of cost, quality and sustainability.

Constraints:

$U_t(Z_t) = b_t + a_t * exp(-c_t Z_t) \quad \forall\, t = 1,2,\dots,T$ *(30)*

This constraint calculates the utility of each group of customer requirements based on the total value of each QFD matrix.

$Z_t = \sum_{i=1}^{m} w_{it} y_{it} \qquad \forall\, t = 1,2,\dots,T$ (31)

This constraint calculates the total value of each group of customer requirements, which is the output of each QFD matrix.

$y_{it} = \sum_{j=1}^{n} R_{ijt} X_j, \qquad \forall\, t = 1,2,\dots,T$ and i=1,2,…,m. (32)

This constraint calculates the value of each CR.

$X_j = h_j + \sum_{k \neq j} T_{kj} h_j \quad \forall\, j = 1,2,\dots,n.$ (33)

This constraint considers the effect of correlations between different design specifications.

$Lb_t \leq Z_t \leq Ub_t \qquad t = 1,2,\dots,T.$ (34)

This constraint makes certain that the final value of each group of customer requirements is between the maximum and minimum values.

$y_{it}^{min} \leq y_{it} \leq y_{it}^{max} \quad \forall\, t = 1,2,\dots,T$ and i=1,2,…,m. (35)

This constraint ensures that the final value of each customer requirements is between the maximum and minimum values.

$0 \leq h_j \leq 1, \ j = 1,2,\dots,n.$ (36)

This constraint ensures that the value of design specification is between the maximum and minimum values.

The objective function is the sum of some convex and concave functions, thus it is a nonconvex function and the model is a nonlinear nonconvex model. We applied the Generalized Reduced Gradient algorithm (GRG) to solve the optimization model. A summary of the methodology is presented in Figure2.

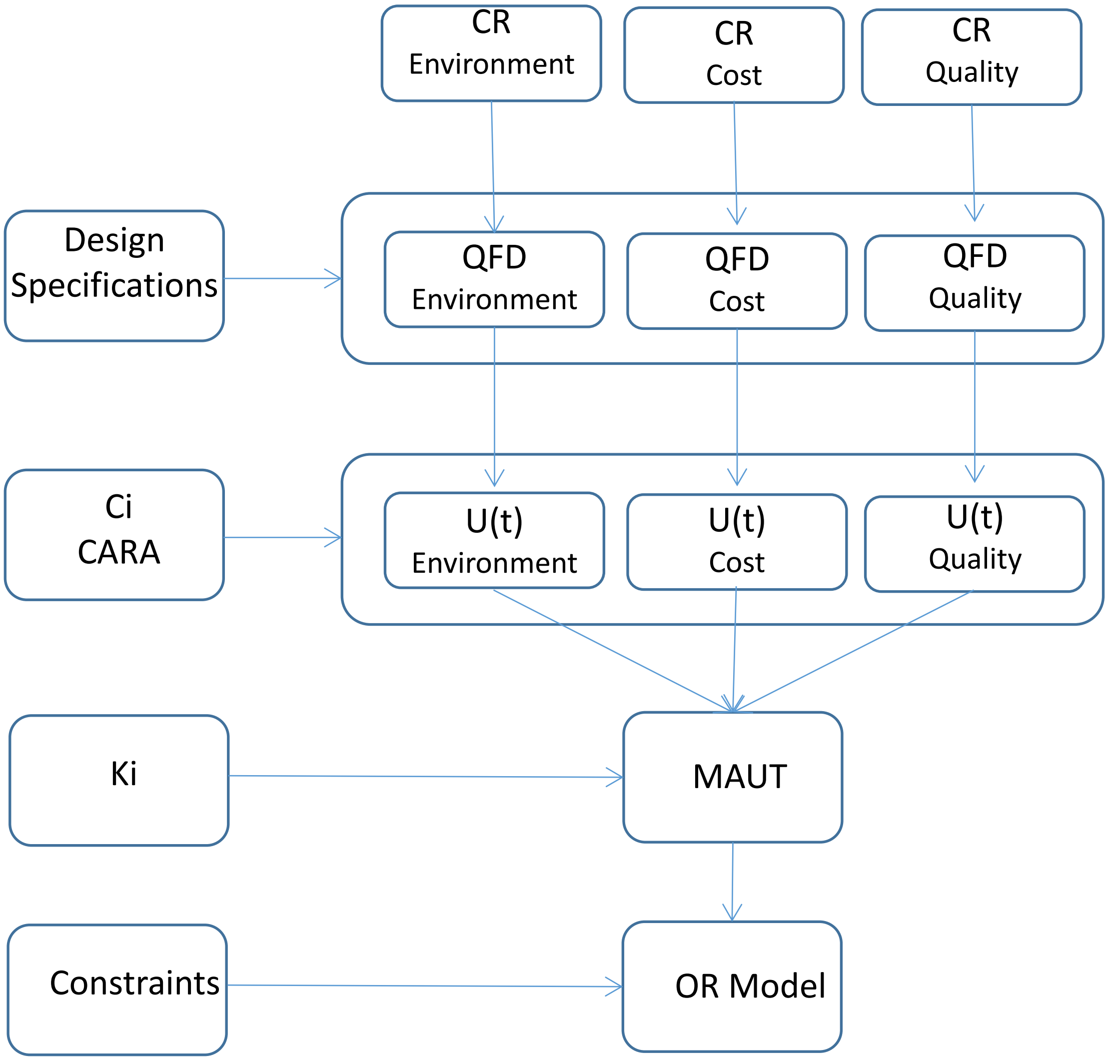

Figure 2. Summary of Methodology

3.4. Case study and calculation

A simple case study revised from what was given by Wassermann (1993) is presented to show how the proposed model works [57]. A pencil-manufacturing firm is going to develop a new product. The example is extended with some modifications.

Table 8. Design specifications

No	Design specifications	Xi,min	Xi,max	Unit [1]
DS1	length	10	20	CM
DS2	time between sharpening	3	6	page
DS3	lead dust generated	1	4	g

DS4	hexagonality	0	100	percentage
DS5	erasure residue	0.005	0.03	mg/cm^2

The design specifications are shown in Table 8.

The correlation between design specifications are obtained from the example which is shown in Table 9. These determine Tkj(s) in our model.

Table 9. Normalize Correlation between DS (Tij) [53]

	DS1	**DS2**	**DS3**	**DS4**	**DS5**
DS1	1	0	0	0	0
DS2	0	1	0.167	0	0.167
DS3	0	0.167	1	0	0.5
DS4	0	0	0	1	0
DS5	0	0.167	0.5	0	1

From a market survey, four major CR's for quality have been identified [57]:

CRQ1. Easy to handle, CRQ2. Does not smear, CRQ3. Point lasts and CRQ4. Does not roll. The QFD matrix for these CR(s) is shown in Table 10.

Table 10. Normalize QFD for quality

normalize QFD for quality (Lyman's normalization)							
	Wight [1,2]		DS1	DS2	DS3	DS4	DS5
Y11	0.17	CRQ1	0.25	0	0	0.75	0
Y12	0.25	CRQ2	0	0.189189	0.405405	0	0.405405
Y13	0.41	CRQ3	0.022026432	0.185022	0.396476	0	0.396476
Y14	0.17	CRQ4	0.1	0	0	0.9	0

Weights of importance for each CR are calculated based on AHP method.

For cost customer requirements as mentioned before, we consider the same costs as the GQFD II, five CR's which cover the life cycle of the product. Therefore the CR's for cost are: CRC1. Material cost, CRC2. Production cost, CRC3. Transportation cost, CRC4. Use cost, and CRC5. End of life cost.

The QFD matrix for these CR(s) is shown in Table 11.

Table 11. Normalize QFD for cost

normalize QFD for cost (Lyman's normalization)							
	Weight		DS1	DS2	DS3	DS4	DS5
Y21	0.21	CRC1	0.052631579	0.252632	0.347368	0	0.347368
Y22	0.21	CRC2	0.272727273	0.3	0.163636	0.090909	0.172727
Y23	0.21	CRC3	1	0	0	0	0
Y24	0.17	CRC4	0	0.126761	0.401408	0.070423	0.401408
Y25	0.2	CRC5	0.652173913	0.217391	0.065217	0	0.065217

As mentioned before for green CR's we consider the LiDS Wheel which has eight categories that each contains a number of basic rules. In this example, we just consider the first level of strategies. It considers the whole lifecycle and indicates significant requirements for each of the steps in the lifecycle. Therefore, the CR's for environment are: CRE1. New Concept Development, CRE2.Selection of low-impact materials, CRE3. Reduction of material, CRE4. Optimization of production techniques, CRE5. Efficient distribution system, CRE6. Reduction of the environmental impact in the user stage, CRE7. Optimization of initial life-time, CRE8. Optimization of end-of-life system.

The QFD matrix for environment CR's is shown in Table 12.

Table 12. Normalize QFD for Environment.

normalize QFD for Environment (Lyman's normalization)							
	Weight		DS1	DS2	DS3	DS4	DS5
Y31	0.08	CRE1	0	0.189189	0.405405	0	0.405405
Y32	0.14	CRE2	0	0.136364	0.443182	0	0.420455
Y33	0.2	CRE3	1	0	0	0	0
Y34	0.1	CRE4	0	0.136364	0.409091	0	0.454545
Y35	0.08	CRE5	1	0	0	0	0

Y36	0.18	CRE6	0	0.266667	0.366667	0	0.366667
Y37	0.15	CRE7	0.056818182	0.528409	0.210227	0	0.204545
Y38	0.07	CRE8	0	0.136364	0.420455	0	0.443182

This is based on expert answers to lottery questions which ask to consider a hypothetical alternative that has equal chances of obtaining a profit of r1 or a loss of r1/2. Then the expert is asked to specify the value of r1 for which s/he would be indifferent between receiving or not receiving the alternative. C1, C2 and C3 are calculated as 0.2, 0.18 and 0.26 respectively which shows degree of risk aversion for each attribute. ki is calculated in the same way based on expert opinions: k1=0.6, k2=0.52 and k3=0.4, therefore K=-0.7855.

For the final model t=1 stands for quality, t=2 stands for cost and t=3 stands for environmental issues. Therefore the final model is as follows:

$\text{Max } U(c) = \frac{1}{K}\{\prod_{t=1}^{3}[Kk_t U_t(Z_t) + 1] - 1\}$ (37)

S.t:

$U_1(Z_1) = 5.5157 - 5.5157 * \exp(-0.2 * Z_1)$ (38)

$U_2(Z_2) = -5.067 + 6.067 * \exp(-0.18 * Z_2)$ (39)

$U_3(Z_3) = 4.366 - 4.366 * \exp(-0.26 * Z_3)$ (40)

$Z_1 = 0.17 * Y11 + 0.25 * Y12 + 0.41 * Y13 + 0.17 * Y14$ (41)

$Z_2 = 0.21 * Y21 + 0.21 * Y22 + 0.21 * Y23 + 0.17 * Y24 + 0.2 * Y25$ (42)

$Z_3 = 0.08 * Y31 + 0.14 * Y32 + 0.2 * Y33 + 0.1 * Y34 + 0.08 * Y35 + 0.18 * Y36 +$

$0.15 * Y37 + 0.07 * Y38$ (43)

Y11= 0.25X1 + 0.75X4 (44)

Y12 = 0.189X2 + 0.405X3 + 0.405X5 (45)

Y13 = 0.022X1 + 0.185X2 + 0.396X3 + 0.396X5 (46)

Y14 = 0.1 X1 + 0.9X4 (47)

Y21 = 0.052X1 + 0.252X2 + 0.347X3 + 0.347X5 (48)

Y22 = 0.27X1 + 0.3X2 + 0.16X3 + 0.09X4 + 0.17X5 (49)

Y23 = X1 (50)

Y24 = 0.126X2 + 0.4X3 + 0.07X4 + 0.4X5 (51)

Y25 = 0.65X1 + 0.21X2 + 0.06X3 + 0.06X5 (52)

Y31 = 018X2 + 0.40X3 + 0.40X5 (53)

Y32 = 0.13X2 + 0.44X3 + 0.42X5 (54)

Y33 = X1 (55)

Y34 = 0.13X2 + 0.4X3 + 0.45X5 (56)

Y35 = X1 (57)

Y36 = 0.26X2 + 0.36X3 + 0.36X5 (58)

Y37 = 0.05X1 + 0.52X2 + 0.21X3 + 0.2X5 (59)

Y38 = 0.13X2 + 0.42X3 + 0.44X5 (60)

$X_j = h_j + \sum_{k \neq j} T_{kj} h_j \quad \forall\, j = 1,2, \dots ,5.$ (61)

$0 \leq h_j + \sum_{k \neq j} T_{kj} h_j \leq 1, \ \forall\, j = 1,2, \dots ,5.$ (62)

$Lb_t \leq Z_t \leq Ub_t \qquad t = 1,2,3.$ (63)

$y_{it}^{min} \leq y_{it} \leq y_{it}^{max} \ \forall\, t = 1,2,3$ and i=1,2,…,m. (64)

$0 \leq h_j \leq 1, \ j = 1,2, \dots ,5.$ (65)

For '+', $h_j = \frac{X_j' - L(X_j)}{U(X_j) - L(X_j)}$ (11)

For '−', $h_j = \frac{U(X_j) - X_j'}{U(X_j) - L(X_j)}$ (12)

After solving the model with the generalized reduced gradient (GRG), the following results obtained that shows the initial optimum value of each design specification in such a way that the total utility for cost, quality and sustainability reached an optimum.

3.5. Results

By solving the model with generalized reduced gradient (GRG), the results in Table 6 for design specifications are achieved. k1 which represents importance of quality has maximum value followed by k2 and k3 which represent cost and sustainability respectively. As we can see in Table 13, Hexagonality reaches its maximum value; this could be because of the highest weight of quality in comparison with cost and sustainability. Length gets its minimum value which can be the result of cost and sustainability. The other design specifications are between maximum and minimum that is the initial optimum value based on the importance and utility of all different customer requirements.

Table 13. Initial optimum values for design specifications.

No	Design specifications	Xi,min	Xi,max	Unit [1]	Initial Optimum value
DS1	Length	10	20	CM	10
DS2	Time between sharpening	3	6	page	5.4220653
DS3	lead dust generated	1	4	g	2.2696566
DS4	Hexagonality	0	100	percentage	100
DS5	Minimum erasure residue	0.005	0.03	mg/cm^2	0.0155805

Table14 shows final values and utilities for each group of customer requirements and also the total utility of the final design. U(i) shows the utility of each group of customer requirements and Z values are outputs of each customer requirements matrix. As we can see in Table 14 the highest utility is for quality followed by environment and cost respectively. It is the same for the output of each customer requirements matrix which makes sense. The only utility under 0.5 is for cost; this is due to the expenses associated with being sustainable and having a high quality. These values are obtained based on the importance that is specified by customers for each group of customer requirements and each CR. If designers consider different weights, possibly the utility of cost will increase while the other two utilities decrease. At this point, a trade-off occurs and designers can check the effects of different changes in the DSs on the final utilities of each group of customer requirements and also total utility of the design.

Table 14. Optimum value for parameters.

Parameter	Value
U(1)	0.9375
U(2)	0.3875
U(3)	0.7373
Z(1)	0.9314
Z(2)	0.5912
Z(3)	0.7114
Total Utility	0.813535

The values for design specifications are the initial optimum values if the importance of quality, cost and sustainability considered as what designer's opinion is indicated. These numbers could be considered as initial values to start with, but designers can modify them if they face new constraints during the PD process. Also as soon as a new constraint is come up designers can consider it in the optimization model or if they face new limit for specific DS, with sensitivity analysis they could easily find the optimum values of the other DS(s).

By using this model, besides making trade-offs between different environmental issues, designers can make trade-offs between environmental issues and other features of new products such as cost and quality. The proposed model does not simply evaluate and compare different proposals, but it also models different specifications of new proposals to determine the optimum point of each.

3.6. Discussion

In the literature review section, the various methods are explained and their limitations are defined. As one can see in the literature, there is limited research that incorporates environmental issues in finding the values of design specifications. Moreover, the tools which work on design specifications for sustainable PD are only able to consider environmental issues to find the best concept between different design concepts, whereas the proposed model helps designers by providing making trade-offs to find the optimal concept based on several sustainability issues and checks the effect of these issues on the other features of the product such as cost and quality. The approach here takes previous efforts one step further by considering environmental, cost and quality requirements in one optimization model to find initial optimum design specifications to start with and improve them for the maximum utility of stakeholders. The customer requirements in each group are compared within each other to facilitate comparison and increase its accuracy, and then trade-offs between three general groups take place by using the MAUT. Cost and sustainability are also considered for the life cycle of the product.

Supporting high level of making trade-off is another differentiation feature of the proposed model besides doing optimization. Byggeth et al (2006) have analyzed different eco-design tools and highlighted the significance of a new eco-design tool having an evaluation method which provides support in trade-off situations [35]. In order to support different trade-off situations, the tool should model criteria in a sustainability perspective and other important aspects e.g. cost, quality [35]. In this study, all the features of the final design are modeled in an optimization model, which after solving, the effects of any changes can be tracked. Designers can check if they increase importance of one feature or a group of CRs, the corresponding effect on other CRs such as quality and cost. Furthermore, by using sensitivity analysis of the model, once designers face a new constraint and have to change a parameter, they can easily check its effect on all others.

In this study utility theory is utilized for the problem of trading off the achievement of one target against one or more other targets and is employed to model the trade-offs between conflicting attributes.

As proposed model calculates the optimum values for design specifications, customer requirements, utility of each group of customer requirements and total utility of stakeholders for different concepts, it provides comprehensive view of the final design in support of making trade-off. It provides a general picture of the final design through the PD process.

3.7. Conclusions

In this study, we recognized three shortcomings of current tools and methods of sustainable PD: weak support of trade-offs, weak connection with the PD process, and lack of life cycle thinking. In the proposed model, we attempt to cover these three shortcomings, mainly weak support of trade-offs. We consider environmental criteria as a group of customer requirements along with quality requirements and cost. Both cost and environment are monitored for the life cycle of the product from material extraction to end of life. The effect of these requirements is modeled in the concept development phase of PD, the most important phase for making trade-offs in the PD process. QFD and AHP is employed for making trade-offs within each group of customer requirements (quality, cost, and environment) and utility theory is used for making trade-offs between the three groups of customer requirements by modeling the stakeholders' goals. Finally, an optimization model is built which models environmental issues, quality and cost in the PD process in order to find their combined optimum level and the optimum level of design specifications. The model is applied to an example and obtained results are explained. The output data shows that trade-offs have been made between different criteria, and also between three groups of CRs. Some DSs achieved their minimum, which is explainable based on the importance of the quality and their cost. The total utility of customers attained its maximum and also correlations between DSs are considered. The results show that optimization model has the potential to help users find optimum design yielding higher customer satisfaction. Furthermore, it can reduce the time of PD process and make the final design more reliable based on stakeholder's opinions.

For the future work, in order to increase the accuracy of the model, the weights could be considered as uncertain weights and this could be done by estimating the distribution of customer's weights. Also, the product development time can be modeled as a constraint in the proposed model. Finally, new groups of customer requirements can be considered.

4. Chapter 4: Making trade-offs to achieve sustainable product development

The fourth chapter consists of the article entitled "Making trade-offs to achieve sustainable product development" was submitted to the *Journal of Cleaner Production* [M. Salari and N. Bhuiyan, August 2017]. The titles, figures, tables, algorithms and mathematical formulations have been revised to the keep the coherence through the thesis.

Abstract

In the literature, various limitations of methods for sustainable product development (PD) are explained. One of the limitations is selecting the best among alternative design concepts. Also, as the nature of the PD process is vague with a high degree of uncertainty, current tools do not pay enough attention to this uncertainty; considering stochastic parameters more realistically reflects PD processes. In this study, the customer requirements of a final design are considered in three groups; cost, quality and sustainability, and are modeled in a stochastic optimization model. Utility theory is applied for trading off the achievement of one target against one or more other targets and modeling the trade-offs between conflicting attributes. The model, by considering stochastic parameters, increases accuracy of making trade-offs among cost, quality and sustainability, along with inspecting different scenarios that are not 100% predictable. As a two-stage stochastic optimization model, it calculates the initial optimum values for design specifications, the utility of each group of customer requirements and total utility of stakeholders for different design concepts. It presents a general picture of the final design in the concept phase of the PD process which helps designers check what would be the corresponding effect of any change in importance of one group of customer requirements such as the environment, on other customer requirement groups such as quality and cost.

4.1. Introduction

Over the past few decades, environmental problems such as the global warming problem (IPCC 2001) and the waste processing problem (OECD 2001) have been quite important. In fact, the environment has become one of the most significant issues for manufacturers. In order to best address these issues, they must be taken into account during product development (PD). The PD process is a set of steps that a company utilize to conceive, design and commercialize a product [74]. This process starts at the extraction of raw materials and takes until end of production. In this process designers make significant decisions since by the end of the PD process, the sustainability attributes of the product are largely fixed [11]

Early decisions in PD will have a significant impact on the sustainability of product realization as the decisions made during PD lock in 70–80% of the total product quality and cost [11, 12]. Much research has been conducted to make PD sustainable, but there still appears to be limitations to their adoption in use. One of the barriers in current tools and methods for sustainable PD is weak support of trade-offs [7]. In PD, there are many elements to consider and trade-offs are necessary when choices have to be made between different alternatives. The tool should be capable of making trade-offs between criteria with a sustainability perspective and other important aspects, e.g. cost and quality [35]. Most of the current tools for sustainable PD can only compare different concepts and cannot make trade-offs to find the optimal concept based on different sustainability issues and verify the effect of these issues on the other features of the product. The most important point of the PD process where trade-offs are made is in the concept phase when defining design specifications based on customer requirements. The sustainability, quality and cost of the product will be largely fixed during this time. This phase consists of the following activities [74], as shown in Figure 3.

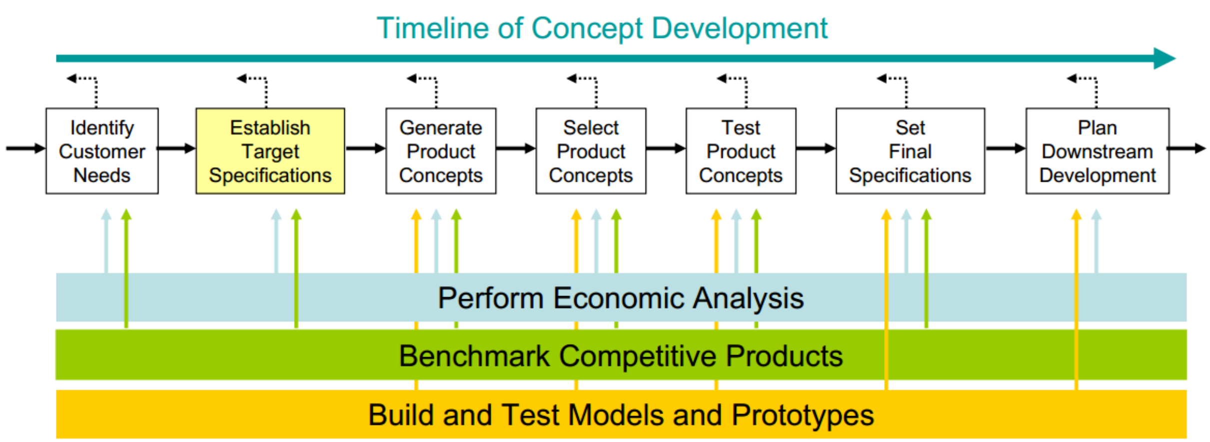

Figure 3. Concept Development [74]

A key feature of an effective design process is careful customer needs or customer requirements assessment, which is the first step in the concept development phase. Traditionally product costs and quality (reliability, functionality, durability etc.) were important for customers, but nowadays, while they remain critical, the environmental impact of a product is increasingly becoming an important issue for companies [75]. Thus, sustainability should be considered as being part of customer requirements, which will then translate into design specifications. Therefore, in this research, we consider sustainability issues as a new group of customer requirements in the concept phase of PD.

The design specifications are the restatement of the design problem in terms of parameters that can be measured. They build a picture of how design decisions affect the customer's perception of the quality, cost and sustainability of the product. These specifications are a translation of the voice of the customer into the technical response of the engineer and they should have units of measure and an associated value [61]. They are defined and improved to meet customer requirements and maximize their satisfaction. This is often done through the implementation of quality function deployment

(QFD), which, with increased product complexity, market competition and limited resources, requires more accurate and optimal solutions. Most of the trade-offs between sustainability and other elements take place in the process of defining specifications and their targets. By finalizing the design specifications, the sustainability, cost and quality of the product are largely finalized. Therefore, this is a critical concern in this research.

The nature of the PD process is vague with a high degree of uncertainty. Uncertainty continues until the prototype is produced, after which it is greatly reduced though not eliminated, and is the main cause of significant rework during the PD process. When designers search for values for design specifications, they begin with imprecise ones. They often begin by defining minimum and maximum values for each design specification. It can be helpful if a model illustrates final satisfaction of customer requirements for any specific group of design specification values, and also can calculate initial optimum values of design specifications to start with in order to have maximum customer requirements satisfaction. It reduces reworks during the PD process as well. To cover this issue, Salari and Bhuiyan (2016) proposed a model to find initial optimum value for design specifications for each design concept in the PD process in order to maximize total utility of customers [60].

This study extends the authors' previous study on the sustainable PD process. Here we improve the accuracy of the solution by modelling a more realistic design process. We consider the weight of the importance of customer requirements to be stochastic to reduce the error in modelling linguistic parameters in numerical models. A two-stage stochastic optimization model is proposed and solved by the Branch-and-Reduce Optimization Navigator (BARON) methodology which is a solver for the global solution of nonlinear (NLP) and mixed-integer nonlinear programs (MINLP). Environmental design is treated as a stochastic optimization model to maximize value-added activities while minimizing environmental effects.

Numerical experiments are proposed to check the improvement of the model, the effect of using stochastic parameters, and to verify the model. The value of the stochastic solution is calculated and the output of a two-stage stochastic model are considered as initial optimum values for design specifications which maximize customer satisfaction. They are considered as the target values for design specifications, which may change during the PD process.

The next section provides the related literature review, while Section 3 presents the methodology and the optimization model. Section 4 describes the case study used, and finally results and conclusions are discussed in Section 5 and 6 respectively.

4.2. Literature review

Much research has been done on how environmental criteria can be integrated into the PD process. Numerous methods and tools have been developed in order to help designers and product developers to consider the environmental effects of the product. The term "tool" and "method" are defined as any type of systematic aid to incorporate the Triple Bottom Line (TBL) aspects into the PD process. Although a vast number of tools have been developed, there still appear to be barriers to their adoption in use. Salari and Buiyan (2016) introduced six major limitations of current PD tools and methods as: 1. weak support of trade-offs; 2. difficulty in learning, understanding, and use; 3. weak connection with the PD process; 4. lack of life cycle thinking; 5. lack of holistic method; 6. and lack of communication [7].

The first and most well-known tool to define design specification values is QFD which has been in use since the 1970's. Our model is based on the QFD and models its output, therefore in this section, related works in using QFD are discussed. Also, a combination of different methods with QFD to define design specification values is considered.

The QFD method was developed in Japan in the mid-1970's and introduced in the United States in 1986 when Kelsey Hayes used it to develop a coolant sensor [61]. A survey of 150 U.S. companies shows that 69% use the QFD method. Of the companies surveyed, 83% perceived that the method had increased customer satisfaction and 76% indicated that it aided logical decisions [61, 67].

Cristofari et al. (1996) developed the methodology of Green QFD (GQFD). They use QFD and LCA to document technical requirements [76]. Different product alternatives will be evaluated based on these requirements so that the best product can be selected [76]. GQFD-II was proposed by Zhang (1999), which integrated LCA and LCC to QFD matrices and deployed customer, costing and environmental requirements throughout the entire PD process [52]. Halog et al (2001) employed QFD with a mathematical model to find out which emissions have to be analysed further for environmental performance improvement. An emission reduction planning model is used to determine how to optimally allocate a cost budget to the various emissions to be reduced for a given technique [66]. Metha and Wang (2001) introduced GQFD III which consists of four phases. They defined GQFD

III to map the voice of the customer (VOC) on technical requirements and compare different concepts based on cost, quality and environmental issues [65].

Enrico and Trucco (2007) proposed the integration Green QFD that is divided into a sequence of partially interactive phases through which an interfunctional development team designs a product that best corresponds to the needs of the target customer, while pursuing an environmental policy. Masui et al (2003) introduce the QFD for the environment (QFDE) as one of the few methods that link the stakeholder requirements to the environmental performance of products [10].

Using QFD for design for the environment has been investigated through several studies [10, 52, 77, 78, 76]. Thus, the effectiveness of the QFD-based methods is widely recognized and we can say QFD is one of the most applicable tools in the PD process.

In the literature, a limited number of researchers have modeled the output of the QFD matrices with mathematical models to optimize a design [69]. Locascio and Thurston (1998) combine quantitative constraints used in design problems with the qualitative design information gathered from QFD to define a multi-attribute design optimization problem where the goal is to maximize customer satisfaction [70]. Rao and Freiheit (1991) use modified game theory to create Pareto optimal solutions to make trade-offs (where improving one goal will cause at least one other to worsen) to the design of a machine tool gear train [64]. Dawson and Askin (1999) define a design problem that allows optimization of non-linear feasibility constraints, correlated engineering characteristics, and non-linear empirical value functions [71]. They propose a non-linear mathematical program for determining the optimal engineering specifications for new product development as a function of extracted customer value functions, engineering development, production costs and development time constraints. Fung et al. (2002) created a fuzzy nonlinear optimization model to find optimum technical attributes [53]. Karsak (2004) utilized the fuzzy Delphi method to determine the level of fulfillment of design requirements and the importance of customers' needs through a fuzzy multiple objective programming.

There is very little research in the literature that considers environmental issues in finding the values of the design specifications. Salari and Bhuiyan (2016) modeled environmental, cost and quality requirements in one optimization model to find optimum design specifications for the maximum utility of stakeholders [60]. They have applied multi-utility theory and QFD to model all design specifications and customer requirements. In this research, stochastic parameters are used in a stochastic optimization model to make the trade-offs between conflicting attributes; therefore, the accuracy of the model is increased since it is more realistic. This research is an improvement of the previous work of the authors by considering customer preference as stochastic parameters.

4.3. Methodology

In this research, environmental features are considered as a new group of customer requirements in the first step of the PD process, which identifies customer needs in the concept development phase. This new group of customer requirements is translated to design specifications and at the same time their effects on other customer requirements is considered. Therefore, during the process of defining values for design specifications, environmental issues along with other concerns will be considered. This ensures the final design could illustrate the effect of reducing the environmental impact on other customer requirements, such as quality and cost of the product, which in turn helps decision makers make better decisions.

The design decision problem is modeled using Multi-Attribute Utility Theory (MAUT), Quality Function Deployment (QFD) and stochastic parameters as described in the following sections.

4.3.1. Quality Function Deployment (QFD)

Converting customer needs into design specifications is one of the most important issues during the design process; in order to maintain market share, designing products that effectively meet or even surpass customers' expectations is vital [70]. QFD identifies the relationships between what the customer wants and what the design team must prepare to provide it [71]. In this research, three QFD matrices are used to transform three groups of customer requirements (quality, cost and environmental issues) into design specifications. The output of each matrix is a function which shows the total value of the respective group of customer requirements [59]. Each QFD matrix has the following parameters:

- $\mathbf{CR}_{it}$ = Customer Requirements for tth matrix, i= 1…m, t= 1,2,3.
- $\mathbf{DS}_j$ = Design Specifications, j= 1…n.
- **Wit =** Weight of importance for ith CRi of tth matrix, t= 1,2,3.
- $\mathbf{R}_{ijt}$ = The strength of the impact of the jth DS towards fulfilling the ith CR for tth matrix, t= 1,2,3.
- $\mathbf{X}_j$ = decision variable for attainment for the jth DS, $X_j \leq 1$ and $X_j = 1$ when the target is reached. Xj has minimum that equal to 0.

For green QFD we use the LiDS Wheel as customer requirements because it considers lifecycle of product and indicates requirements for each step in the lifecycle [28]. The Lifecycle Design Strategies or LiDS Wheel is among the well-known and easy to use tools in environmental design. It includes eight categories that each contains a number of basic rules which follow the lifecycle of the product from resource acquisition to waste disposal. For cost requirements, we consider the same as GQFD-II [52], for which the five major CR(s) for the cost matrix are: material cost, production cost, transportation cost, use cost and end of life cost.

Each of the DS(s) has a direct or indirect impact which is defined as either '+' (more is better) or '−' (less is better). All design specifications are scaled to 0 to 1 using the following formulas [59]:

For '+', $X_j' = \frac{X_j - L(X_j)}{U(X_j) - L(X_j)}$ (66)

For '−', $X_j' = \frac{U(X_j) - X_j}{U(X_j) - L(X_j)}$ (67)

Where $U(X_j)$ and $L(X_j)$ are the upper and lower bounds of X_j.

We can model the QFD matrices as:

Max Z = $\sum_{i=1}^{m} w_i y_i$ (68)

S.T: $y_i = \sum_{j=1}^{n} R_{ij} X_j'$, i=1,2,…,m (69)

$X_j' = f_j(X_1', X_2', \ldots, X_n') \leq 1, j = 1,2, \ldots, n$ (70)

The correlation between design specifications is defined by a scale of 0, ±1, ±3, ±9, 18. A value of 18 is simply for the correlation between the same DS [53]. T_{ij} denotes dependence of the i^{th} DS on the j^{th} DS. There is no dependence when T_{ij}=0. When T is normalized, $T_{ij} \in [-1,1]$ and T_{ii} =1.

The final X_j' will be calculated as follows [59]:

- **h_j** = the planned attainment for the j_{th} DS,

$X_j' = h_j + \sum_{k \neq j} T_{kj} h_j = \sum_{k=1}^{n} T_{kj} h_j.$ (71)

S.t:

$0 \leq h_j + \sum_{k \neq j} T_{kj} h_j \leq 1, \ j = 1,2, \ldots, n.$ (72)

To improve the model and model uncertainty along with increased accuracy in the final results, we applied stochastic parameters in the weighting factors. The weighting factors (W_i) show the importance of each CR in the Z value of each category of customer requirements. They are calculated based on the customer's opinions, which are often linguistic and imprecise. This qualitative data must be translated into numerical scales.

In this study to increase accuracy and reduce error of using this linguistic parameter, we consider W_i as a stochastic parameter. For this purpose, each completed survey (opinion of each customer), is considered as one scenario for W as stochastic parameter. Also, we can use estimated distribution for each W_i. In the case study, we applied each customer opinion as one scenario.

4.3.2. Multi-Attribute Utility Theory (MAUT)

Design specification optimization is a complicated decision-making problem. The complexity comes from a multitude of quantitative and qualitative factors as well as the internal difficulty of making numerous trades-offs among these factors [59]. In order to handle this complexity, we apply Multiple-Attribute Utility Theory (MAUT). MAUT is an analytical method based on multiple criteria for decision-making, and was proposed by Keeney and Raiffa (1976) [56]. In this study we define three exponential utility functions for three goals (environment, quality and cost) in a constant absolute risk aversion (CARA) set-up as $u(x) = -\exp(-x/c)$ where c is a positive constant, and has the nature of constant absolute risk aversion (CARA).

Therefore, the utility function U is exponential and is defined as:

$U_i(Z_i) = b_i + a_i * \exp(-c_i Z_i)$. (73)

Z_i is calculated based on QFD matrices and shows the utility of producers for each group of customer requirements.

The final utility U(x) which is an outcome of attributes (cost, quality and environment) can be acquired from the solution to the following equation [55]:

$$U(x) = \frac{1}{K}\{\prod_{i=1}^{n}[Kk_iU_i(x_i) + 1] - 1\} \quad (74)$$

K is a scaling constant which is a solution to: $-1 < K < 0$

$$1 + K = \prod_{i=1}^{n}[Kk_i + 1] \quad (75)$$

4.3.3. Optimization model

Three goals are defined and combined into one objective function by MAUT. By considering the weighting factors as stochastic parameters, we have a stochastic optimization problem.

Two-stage stochastic programming is appropriate for cases where the random parameters have stationary behavior over time. In this case W_i can be approximated as a set of scenarios which are not dynamic over time, therefore our model is a two-stage stochastic problem.

The extended two-stage stochastic model is presented as follows.

Objective function:

$U(c): total\ utility\ of\ customers\ for\ three\ attributes: quality, cost\ and\ environment$

First Stage Decision variables:

$h_j: the\ planned\ attainment\ for\ jth\ DS$

$X_j: attainment\ for\ jth\ DS$

$y_{it}: value\ for\ ith\ CR\ of\ tth\ attribute$

Second Stage Decision variables:

$Z_{ts}: value\ of\ tth\ attribute\ for\ sth\ senario$

$U_{ts}(Z_{ts}): utility\ of\ tth\ attribute\ for\ sth\ senario$

Parameters:

$P_s: probability\ of\ S^{th}\ senario\ happening$

$K: scaling\ constant$

$k_t: weighting\ for\ each\ attribute$

$a_t, b_t: parameters\ to\ scale\ U_t(Z_t)\ from\ 0\ to\ 1$

$c_t: degree\ of\ risk\ aversion$

$w_{its}: weight\ of\ importance\ for\ the\ i^{th}\ CR_i\ of\ t^{th}\ attribute\ for\ S^{th}\ senario$

$R_{ijt:}\ the\ strength\ of\ the\ impact\ of\ the\ j^{th}\ DS\ towards\ fulfilling\ the\ i^{th}\ CR$

$for\ tth\ attribute$

$T_{kj}: degree\ of\ dependence\ of\ the\ k^{th}\ DS\ on\ the\ j^{th}\ DS$

$Lb_{ts}: the\ minimal\ acceptable\ satisfaction\ level\ of\ attribute\ t\ for\ s^{th}\ senario$

$Ub_{ts}: the\ maximal\ acceptable\ satisfaction\ level\ of\ attribute\ t\ for\ s^{th}\ scenario$

$y_{it}^{max}, y_{it}^{min}$: the minimal and maximal acceptable satisfaction level of CR_i (if any of the customer requirements has minimum or maximum, it will show up in the constraints)

$$Max\ U(c) = \frac{1}{K}\{\prod_{t=1}^{T}[Kk_t \sum_{s=1}^{S} P_s\, U_{ts}(Z_{ts}) + 1] - 1\} \qquad (76)$$

S.t:

$$U_{ts}(Z_{ts}) = b_t + a_t * exp(-c_t Z_{ts}) \quad \forall\, t = 1,2,\dots,T \text{ and } s = 1,2,\dots,S \qquad (77)$$

$$Z_{ts} = \sum_{i=1}^{m} w_{its} y_{it} \qquad \forall\, t = 1,2,\dots,T \text{ and } s = 1,2,\dots,S \qquad (78)$$

$$y_{it} = \sum_{j=1}^{n} R_{ijt} X_j, \qquad \forall\, t = 1,2,\dots,T \text{ and } i=1,2,\dots,m. \qquad (79)$$

$$X_j = h_j + \sum_{k\neq j} T_{kj} h_j \quad \forall\, j = 1,2,\dots,n. \qquad (80)$$

$$0 \le h_j + \sum_{k\neq j} T_{kj} h_j \le 1, \ \forall\, j = 1,2,\dots,n. \qquad (81)$$

$$Lb_{ts} \le Z_{ts} \le Ub_{ts} \qquad t = 1,2,\dots,T \text{ and } s = 1,2,\dots,S. \qquad (82)$$

$$y_{it}^{min} \le y_{it} \le y_{it}^{max} \quad \forall\, t = 1,2,\dots,T \text{ and } i=1,2,\dots,m. \qquad (83)$$

$$0 \le h_j \le 1, \ j = 1,2,\dots,n. \qquad (84)$$

For '+', $h_j = \frac{X_j' - L(X_j)}{U(X_j) - L(X_j)}$ (66)

For '–', $h_j = \frac{U(X_j) - X_j'}{U(X_j) - L(X_j)}$ (67)

The output of the model is considered as initial optimum values to start with a concept. This model is more accurate than when we consider weights as deterministic parameters. As mentioned before, the process of PD is vague and part of this vagueness comes from linguistic parameters like weight of importance by customer opinions which cause designers do not have any idea of what could be initial values for the DSs to start. This model calculates optimum points to start with, which we call the "initial optimum values". It helps designers during the PD process to easily check and track the effect of any changes in parameters on the other DSs, and also to determine the utility of cost, quality and sustainability and their combination.

Constraints:

$U_{ts}(Z_{ts}) = b_t + a_t * exp(-c_t Z_{ts}) \quad \forall\, t = 1,2,\dots,T \; and \; s = 1,2,\dots,S$ *(77)*

This constraint calculates the utility of each scenario for each group of customer requirements based on the total value of each QFD matrix.

$Z_{ts} = \sum_{i=1}^{m} w_{its} y_{it} \qquad \forall\, t = 1,2,\dots,T \; and \; s = 1,2,\dots,S$ *(78)*

This constraint calculates the total value of each group of customer requirements for each scenario, which is the output of each QFD matrix.

$y_{it} = \sum_{j=1}^{n} R_{ijt} X_j, \qquad \forall\, t = 1,2,\dots,T \; and$ *i=1,2,…,m.* *(79)*

This constraint calculates the value of each customer requirement.

$X_j = h_j + \sum_{k \neq j} T_{kj} h_j \quad \forall\, j = 1,2,\dots,n.$ (80)

This constraint calculates the effect of correlations between different design specifications.

$Lb_{ts} \le Z_{ts} \le Ub_{ts} \qquad t = 1,2,\dots,T \; and \; s = 1,2,\dots,S.$ *(81)*

This constraint ensures that the final value of each group of CRs is between the maximum and minimum values.

$y_{it}^{min} \le y_{it} \le y_{it}^{max} \quad \forall\, t = 1,2,\dots,T \; and$ *i=1,2,…,m.* *(82)*

This constraint makes certain that the final value of each CR is between the maximum and minimum values.

$0 \le h_j \le 1, \; j = 1,2,\dots,n.$ (83)

This constraint ascertains that the value of the design specification is between the maximum and minimum values.

Index S indicates different scenarios. The objective function is the sum of some concave and convex functions, thus it is a nonconvex function and the model is a nonlinear nonconvex model. We applied the Branch-and-Reduce Optimization Navigator to solve the optimization model.
BARON is a GAMS solver for the global solution of nonlinear (NLP) and mixed-integer nonlinear programs (MINLP). Nonlinear programing algorithms are guaranteed to find global optimum only

under convexity assumptions, while BARON uses deterministic global optimization algorithms of the branch-and-bound type that is ensured to find global optima under general assumptions. These assumptions include the existence of finite lower and upper bounds on nonlinear expressions in the MINLP or NLP to be solved. BARON applies algorithms of the branch-and-bound type improved by a variety of constraint propagation, interval analysis, and duality techniques for reducing ranges of variables in the course of the algorithm.

As all our decision variables are bounded between zero to one, so all nonlinear expressions in our optimization model are bounded, therefore BARON conditions are meet in this model. The software which used to run this solver method is GAMS, and we coded the model and ran it for the case study.

4.4. Case study and calculation

The case study here is stochastic model of a case as presented by Salari & Bhuiyan (2016) [60], which was a revised version used by Wassermann (1993) [57]. We used the same case, and modify deterministic weights to stochastic one. Here instead of using AHP and converting all weights to one final weight we use all different scenarios of customer opinions and finally compare the stochastic solution with the deterministic one was presented by Salari and Bhuiyan (2016) [60]. The case is about a pencil-manufacturing firm which is developing a new product. It has five design specification and three groups of customer requirements as cost, quality and sustainability. Following each group of CR, design specifications and values are explained.

The design specifications and correlation among them are shown in Tables 15 and 16 respectively.

Table 15. Design specifications

No	Design specifications	X_i,min	X_i,max	Unit [1]
DS1	length	10	20	CM
DS2	time between sharpening	3	6	page
DS3	lead dust generated	1	4	g
DS4	hexagonality	0	100	percentage
DS5	erasure residue	0.005	0.03	mg/cm^2

Table 16. Normalize Correlation between DS (Tij) [53]

	DS1	DS2	DS3	DS4	DS5
DS1	1	0	0	0	0
DS2	0	1	0.167	0	0.167
DS3	0	0.167	1	0	0.5
DS4	0	0	0	1	0
DS5	0	0.167	0.5	0	1

For quality, four major CR's have been recognized from a market survey [57]:
CRQ1. Easy to handle, CRQ2. Does not smear, CRQ3. Point lasts and CRQ4. Does not roll. The QFD matrix for these CR(s) is shown in Table 17.

Table 17. Normalize QFD for quality

		DS1	DS2	DS3	DS4	DS5
Y11	CRQ1	0.25	0	0	0.75	0
Y12	CRQ2	0	0.189189	0.405405	0	0.405405
Y13	CRQ3	0.022026432	0.185022	0.396476	0	0.396476
Y14	CRQ4	0.1	0	0	0.9	0

Weights of importance for each CR are gathered by distributing a survey to 30 customers. Each survey is considered as a scenario. Therefore, a set of 30 scenarios are considered for the stochastic model as a set of Wits, where S= {1...30} represents customer responses.
The CR's for cost are: Material cost, Production cost, Transportation cost, Use cost, and End of life cost.
The QFD matrix for these CR(s) is shown in Table 18.

Table 18. Normalize QFD for cost

		DS1	DS2	DS3	DS4	DS5
Y21	CRC1	0.052631579	0.252632	0.347368	0	0.347368
Y22	CRC2	0.272727273	0.3	0.163636	0.090909	0.172727
Y23	CRC3	1	0	0	0	0

Y24	CRC4	0	0.126761	0.401408	0.070423	0.401408
Y25	CRC5	0.652173913	0.217391	0.065217	0	0.065217

Green CR's are considered like the LiDS Wheel which has eight categories. In this example, we consider only the first level of strategies. Therefore, the CR's for environment are: New Concept Development, Selection of low-impact materials, Reduction of material, Optimization of production techniques, Efficient distribution system Reduction of the environmental impact in the user stage, Optimization of initial life-time, and Optimization of end-of-life system. These eight strategies are green criteria as a package that follows the life cycle of the product.
The QFD matrix for environment CR's is shown in Table 19.

Table 19. Normalize QFD for Environment

		DS1	**DS2**	**DS3**	**DS4**	**DS5**
Y31	CRE1	0	0.189189	0.405405	0	0.405405
Y32	CRE2	0	0.136364	0.443182	0	0.420455
Y33	CRE3	1	0	0	0	0
Y34	CRE4	0	0.136364	0.409091	0	0.454545
Y35	CRE5	1	0	0	0	0
Y36	CRE6	0	0.266667	0.366667	0	0.366667
Y37	CRE7	0.056818182	0.528409	0.210227	0	0.204545
Y38	CRE8	0	0.136364	0.420455	0	0.443182

Ci(s) and Ki(s) are calculated based on expert answers to lottery questions, as explained in detail by [59]: C1=0.2, C2= 0.18 and C3=0.26 show degree of risk aversion for each attribute. k1=0.6, k2=0.52 and k3=0.4 determine the weight of each attribute, therefore K=-0.7855.
In the model, t=1 stands for quality, t=2 stands for cost and t=3 stands for environmental issues. Therefore the final extended model is as follows:

$$\text{Max } U(c) = \frac{1}{K}\{\prod_{t=1}^{3}[Kk_t \sum_{s=1}^{30} P_s\, U_{ts}(Z_{ts}) + 1] - 1\} \quad (84)$$

subject to:

$$U_{1s}(Z_{1s}) = 5.5157 - 5.5157 * \exp(-0.2 * Z_{1s}) \quad s = 1,2,\dots,30 \quad (85)$$

$U_{2s}(Z_{2s}) \ = \ -5.067 \ + \ 6.067 * \exp(-0.18 * Z_{2s}) \quad s = 1,2,\dots,30$ (86)

$U_{3s}(Z_{3s}) \ = \ 4.366 \ - \ 4.366 * \exp(-0.26 * Z_{3s}) \quad s = 1,2,\dots,30$ (87)

$Z_{1s} = \sum_{i=1}^{m} w_{i1s} y_{i1} \quad \forall\, s = 1,2,\dots,30$ (88)

$Z_{2s} = \sum_{i=1}^{m} w_{i2s} y_{i2} \quad \forall\, s = 1,2,\dots,30$ (89)

$Z_{3s} = \sum_{i=1}^{m} w_{i3s} y_{i3} \quad \forall\, s = 1,2,\dots,30$ (90)

Y11= 0.25X1 + 0.75X4 (91)

Y12 = 0.189X2 + 0.405X3 + 0.405X5 (92)

Y13 = 0.022X1 + 0.185X2 + 0.396X3 + 0.396X5 (93)

Y14 = 0.1 X1 + 0.9X4 (94)

Y21 = 0.052X1 + 0.252X2 + 0.347X3 + 0.347X5 (95)

Y22 = 0.27X1 + 0.3X2 + 0.16X3 + 0.09X4 + 0.17X5 (96)

Y23 = X1 (97)

Y24 = 0.126X2 + 0.4X3 + 0.07X4 + 0.4X5 (98)

Y25 = 0.65X1 + 0.21X2 + 0.06X3 + 0.06X5 (99)

Y31 = 018X2 + 0.40X3 + 0.40X5 (100)

Y32 = 0.13X2 + 0.44X3 + 0.42X5 (101)

Y33 = X1 (102)

Y34 = 0.13X2 + 0.4X3 + 0.45X5 (103)

Y35 = X1 (104)

Y36 = 0.26X2 + 0.36X3 + 0.36X5 (105)

Y37 = 0.05X1 + 0.52X2 + 0.21X3 + 0.2X5 (106)

Y38 = 0.13X2 + 0.42X3 + 0.44X5 (107)

$X_j = h_j + \sum_{k \neq j} T_{kj} h_j \quad \forall\, j = 1,2,\dots,5.$ (108)

$0 \leq h_j + \sum_{k \neq j} T_{kj} h_j \leq 1, \ \forall\, j = 1,2,\dots,5.$ (109)

$Lb_{ts} \ \leq \ Z_{ts} \ \leq Ub_{ts} \quad t = 1,2,3 \text{ and } s = 1,2,\dots,30$ (110)

$y_{it}^{min} \leq y_{it} \leq \ y_{it}^{max} \ \ \forall\, t = 1,2,3$ and i=1,2,…,m. (111)

$0 \leq h_j \leq 1, \ j = 1,2,\dots,5.$ (112)

For ‘+’, $h_j = \frac{X_j' - L(X_j)}{U(X_j) - L(X_j)}$ (66)

For ‘−’, $h_j = \frac{U(X_j) - X_j'}{U(X_j) - L(X_j)}$ (67)

After solving the model with the generalized reduced gradient (BARON), the initial optimum value for each design specification is obtained while considering all scenarios of weights in such a way that the total utility reached its maximum.

4.5. Results

By solving the model, the results in Table 6 for design specifications are achieved. The total utility (Zobj) for the optimal solution of the extended two-stage stochastic model is obtained 0.78143=Opt. Salari and Bhuiyan (2016) solved the deterministic model of the same problem, which we consider as the expected value problem for the two-stage stochastic model of this paper [60]. If we use the solution of the expected value problem and calculate the value of the objective function of the two-stage stochastic model, we will obtain 0.71422. We use this solution as the lower bound of the deterministic model (Lbdet) to calculate the value of the stochastic solution (VSS).
Therefore, the VSS is calculated as follows:

VSS = 100(Opt-Lbdet)/Lbdet   VSS = 9.41%

The percentage of VSS shows that if we consider the weight of customers as stochastic parameters rather than deterministic we will get 9.41% more utility on the final design.
Table 20, shows the optimum values for design specifications if we solve the model by considering weights as stochastic parameters. The result shows length and hexagonality reach their minimum and maximum value respectively which could be because of the importance of quality and cost. The rest of the design specifications are between the maximum and minimum that are considered as the initial optimum value of design specifications to continue PD process.

Table 20. Initial optimum values for design specifications.

No	Design specifications	X_i,min	X_i,max	Unit [1]	Initial Optimum value
DS1	Length	10	20	CM	10
DS2	time between sharpening	3	6	page	4.4269812
DS3	lead dust generated	1	4	g	2.5166281

DS4	Hexagonality	0	100	percentage	100
DS5	Minimum erasure residue	0.005	0.03	mg/cm^2	0.0196571

If designers consider different weights for each group of customer requirements (ki), possibly the utility of each group of customer requirement and also total utility will be affected. Therefore a trade-off occurs and designers can check the effects of each change on the total utility of the final design.
These values of design specifications are the initial optimum values if all different scenarios for customer opinions applied. These are initial values to start with, but if designers face new constraints during the PD process, they can modify them. Therefore, by using this model, designers can make trade-offs between cost, quality and environmental issues of new products and model different specifications of new proposals to determine the optimum point of each.
Although, in the literature, there is some research on modeling the output of the QFD matrix, none applied stochastic parameters in analysing QFD output. In this research, the case study shows that by using weights of customers as stochastic, we can increase the total utility of customers by almost 10%. Since the weights of customers are linguistic parameters, it is better to not consider them in the model as a deterministic number, which would not be a good representation. Using each series of weights as a scenario in a two-stage stochastic model helps to increase the realism and reduces the error in the final results.
The main benefit of using a stochastic model instead of deterministic one is modeling more uncertainty by considering different scenarios in terms of customer opinions.

4.6. Conclusions

In this study we improved a previous model by Salari and Bhuiyan (2016) by using uncertain parameters in the model to treat an actual case more realistically. The proposed model covers three shortcomings: weak integration of environmental tool with the PD process, weak support of trade-offs and lack of life cycle thinking. This is done by considering environmental criteria for the life cycle of a product from material extraction to end of life as a group of customer requirements, along with quality and cost requirements. This model is proposed for use in the concept development phase of PD, which is the starting point for making trade-offs in the PD process. QFD and utility theory are used to make trade-offs within each group of customer requirements (cost, quality and environment) and among the three groups of customer requirements by modeling the stakeholders' goals. The weights of customer requirements are considered as stochastic parameters to make customer opinions more realistic, and finally a stochastic optimization model is proposed that models quality, environmental issues and cost in the PD process in order to find the optimum level of design specifications.

The model is applied to the case study from Salari and Bhuiyan (2016), used in their deterministic model. The output data shows that the VSS is around 10%, meaning if we consider weights as stochastic parameters, we will obtain 10% better results on the total utility of customers for the final design. Thus, the stochastic optimization model has the potential to help designers find optimum design specifications yielding higher customer satisfaction. Furthermore it can make the final design more reliable based on customer's opinions. Since weights are linguistic parameters, using stochastic parameters instead of deterministic ones improves the model and increases the accuracy of the final optimum result.

For future work, the problem can be modelled through robust optimization to have better estimation on the distribution of stochastic parameters and also to have more control on the cost of the objective function. Also in order to increase the accuracy of the model, the weights of each attribute (k_i) could also be considered as stochastic parameters.

Finally, the duration of the PD process can be added to the model as a new constraint to select the optimum concept with reasonable PD time. It helps to not deliver a new product late on the market and also to have more control on the cost of PD.

5. Chapter 5: Conclusion and Future Work

In this thesis, we investigated the modeling of the product development process while considering sustainability issues for the whole life cycle of the product. At first, we focused on a scoring model by covering three shortcomings in the literature. Then, we considered an optimization model which has the capability of making trade-offs during the product development process, and finally we consider uncertainty for weights of customer requirements and propose a two-stage stochastic optimization model.

The remainder of this chapter provides concluding remarks of this research provided in each chapter. Then, several avenues for future work following this dissertation are presented, and contributions of this work to the existing body of work are summarized.

5.1. Concluding Remarks

The objective of this thesis is to study how to integrate sustainability into the product development process. Based on the literature review, barriers and limitations of current methods of sustainable product development are defined and targeted. One of the limitations exposed in the literature is the lack of integration of sustainability within the PD process, and no general model which covers the full product life cycle. In this thesis, holistic sustainability criteria are selected and considered as a group of customer requirements. Three groups of customer requirements, cost, quality and environment, are translated into design specifications; in this way, design specifications are actually defined based on the importance of each group, importance of the criteria within each group and considering the correlation between the criteria in each group. Both cost and environmental issues are monitored for the life cycle of the product from material extraction to end of life.

A scoring model is proposed to evaluate different concepts in the concept development, the second phase of the product development process. The model provides a value for each concept that presents level of satisfaction of customer requirements and their total utility to customers. The proposed model helps designers compare various concepts and select the best among them. To build the model, a QFD matrix is used to translate customer requirements into design specifications, and multi-attribute utility theory is applied to evaluate customer requirement satisfaction and the utility of each group of customer requirements. The model is applied to a case study in the development of a pencil, where three concepts are compared and the concept with highest utility has been selected. Therefore, the contribution to the literature in first article is proposing a holistic model which consider cost, quality and sustainability for the whole life cycle of the product while it is integrated into the PD process.

There is limited research optimising design specifications while considering environmental issues. Moreover, none of them considers environmental issues in addition to customer requirements like cost and quality to optimize design specifications. The proposed model in the second article helps designers to find the optimal concept based on sustainability, cost and quality while making trade-offs between these customer requirements. The customer requirements in each group are compared with each other to facilitate comparison and increase accuracy, and then trade-offs between three general groups take place by using the MAUT. Another limitation for sustainable product development tools and methods is making trade-offs during the PD process. The proposed model provides the ability to make trade-offs for designers through the product development process. It provides an initial optimum value to start with and during the process they can make trade-offs between customer requirements satisfaction and design specification values. By modeling the product development process as an optimization model, designers get an idea of the approximate value for each design specification to begin with, and by using sensitivity analysis, they can make trade-offs between design specifications and customer requirements. Sensitivity analysis helps designers determine the effect of any change in design specification values on other design specifications and customer requirements, which is helpful towards reducing rework, and in turn helping to be more lean in the PD process. Also, design constraints such as budget are modeled to be limited between its lower and upper bound. The final model is non-linear non-convex with certain conditions, which was solved with the BARON solution. It is applied to the same case study of the pencil design, and optimum values for each design specification, the utility of each group of customer requirements and the total utility of the final design is achieved. The results show that the optimization model has the potential to help users find an optimum design yielding higher customer satisfaction. Furthermore, it can reduce the time of the PD process.

The contribution in third article is the consideration of the weight of customer requirements as uncertain parameters, something not previously considered in the literature before. This allows the model to be more realistic in comparison to a deterministic model. since the weight of customer requirements are linguistic parameters, and it is hard to replace linguistic parameters with a fixed number; thus they are considered as uncertain parameters. Thus, a stochastic optimization model is proposed by using each customer's opinion for weights as a unique scenario in the model. The solution of the model in chapter three is used as the expected value for this stochastic model and by using this solution in the objective function of the two-stage stochastic model, the lower bound of the stochastic model is calculated. By applying this lower bound, the VSS is obtained as 9.41%, which shows that by considering weights as uncertain parameters, we could achieve approximately 10% better on the total utility to customers.

In summary, we previously identified shortcomings of current tools and methods for sustainable product development in six categories. This research covers three of them, namely weak integration of environmental tool with the PD process, weak support of making trade-offs, and lack of life cycle thinking, and offers the following contributions to the literature to overcome these weaknesses:

- A holistic model which considers sustainability in addition to cost and quality for the whole life cycle of the product, integrated to the PD process.
- An optimization model to find the optimum value of design specifications by considering three groups of customer requirements (Cost, Quality and Sustainability).

- The ability to make trade-offs for designers during the PD process, which helps them track effects of any changes on all design parameters during the PD process.
- Consideration of the weight of each customer requirements as uncertain parameter and proposing stochastic model which has almost 10% improvement versus deterministic model.

5.2. Future Research Directions

This research can be extended in a number of directions.

- Applying robust optimization would allow for better estimation on the distribution of the uncertain parameter and the cost of the objective function would be under more control.
- Considering other types of uncertain parameters, such as the weights of each attribute (k_i), and examining how they will affect the optimal solution is subject to further investigation. The uncertainty in the impact of each design specification on customer requirements can be an interesting extension of this study as well.
- Studying different heuristic methods to solve the problem would also be an extension of this thesis. For the small case study we used here, it takes almost one hour to find the optimal solution, but for designs with more customer requirements and design specifications, it would take much longer. Therefore, working on a heuristic solution to make searching for an optimum solution more efficiently would be valuable to extend this research.
- In closing, we provided some insights on modeling the duration of the PD process as a new constraint in order to select the optimum concept with reasonable PD time. It helps to have more control on the cost of product development and not deliver late on the market.

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