Eco-Design Improvement at the Conceptual Design Stage: Methodology and Applications

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Abstract

Eco-Design Improvement at the Conceptual Design Stage: Methodology and Applications

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While quality tools are familiar to industries for the continuous improvement of products, the associated tools can be adopted to make significant contributions that address environmental concerns. This aligns eco-design with the product improvement process. This thesis proposes an eco-design improvement method, in which the eco-design tools are systematically integrated for the purpose of reducing environmental impacts. In this context, this work focuses on the adaptations of quality tools for supporting the generation of new eco-design concepts.

The developed methodology consists of three major phases. The first phase is concerned with the development of a relational matrices model. This phase is intended to explicitly capture the information of an existing design via relational models. These models are based on the integration of quality function deployment (QFD) and functional analysis (FA). The QFD process requires mapping quality attributes and design attributes to identify the attributes' relationships to the existing design. The integration approach used is based on developed relational matrices to capture the relationships among environmental requirements, engineering metrics, design functions and physical components. In addition, FA focuses on functional decomposition of a design to support the generation of design concepts. One important feature of this phase is to connect the environmental requirements to the design functions.

The second phase is concerned with the generation of design concepts. In this phase, after identifying the functions that are responsible for reducing environmental impacts, a morphological chart is used to support the synthesis of new design concepts. The third phase considers environmental impact assessments and concept selection. In this phase, two methods are developed: Pugh chart and fuzzy assessment. The Pugh chart is intended to evaluate the newly generated concepts via the delegated engineering metrics. As well, fuzzy assessment is intended to capture the imprecise design information at the conceptual design stage. To address this research problem using fuzzy assessments, the trapezoidal fuzzy numbers are first applied to capture imprecise design information for each design concept. A decision guide is also proposed to suggest a course of action based on the results of fuzzy assessments. This phase is also concerned with ways to incorporate such imprecise information with eco-indicators for decision making.

Finally, for the demonstration and validation, the proposed methodology is applied to three case examples. These examples are in two different contexts. The methodology is first applied to home appliances, which are a coffee maker and hair dryer. Then, the suggested methodology is extended to the forming processes, specifically, the diaphragm forming process (DFP). This application of the diaphragm process is demonstrated through the assessment of the energy consumption of the usage stage. The developed methodology illustrates potential reduction in energy consumption for the generated designs of the applied examples. The results show the applicability of the proposed methodology.

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Last but not least, may Allah bless us with his love and make this work purely for his sake and bless all we do.

Table of Contents

List of Figures

List of Tables

List of Symbols

a	Engineering quantity
$a(x)$	Value of quantity 'a'
a_1	The lower bound
a_2, a_3	The range of typical values
a_4	The upper bound
AC	Alternating current
BOM	Bill of materials
C	Components
CMC	Comparison among multiple concepts
COD	Comparison with original design
d_c	Centroid point (balanced)
DC	Direct current
DEA	Data envelopment analysis
DFE	Design for environment
DFP	Diaphragm forming process
d_o	Centroid point (optimistic)
d_{or}	Distance from the origin
d_p	Centroid point (pessimistic)
E	Engineering quantity
ECQFD	Environmentally conscious QFD
EM	Environmental metrics

F	Functions
Fa	Fuzzy number of quantity '*a*'
FA	Functional analysis
FC	Relational matrix of functions and components
FC^T	Matrix transpose of functions and components
fc_{ij}	Function-component matrix
i_a	Eco-indicator of the quantity '*a*'
$I(x)$	Overall impact assessment of concept '*x*'
LCA	Life cycle assessment
LCI	Life-cycle inventory
M	Metrics
MC	Relational matrix of metrics and components
mc_{ij}	Metric-component matrix
ori	Original design
QFD	Quality function deployment
QFDE	QFD for Environment
R	Requirements
RF	Relational matrix of requirements and functions
rf_{ij}	Requirement-function matrix
RF_n	Requirement-function matrix after normalization
RM	Relational matrix of requirements and metrics
rm_{ij}	Requirement-metric matrix
RPM	Revolution per minute

s	Same
TFN	Triangular fuzzy numbers
TrFN	Trapezoidal fuzzy numbers
TRIZ	Theory of inventive problem solving
VoC	Voice of customer
VoE	Voice of environment
w	A scalar
x_c, y_c	Centroid point of the trapezoidal
x_o, y_o	Optimistic point of the trapezoidal
x_p, y_p	Pessimistic point of the trapezoidal
$\mu(a)$	Membership function

Chapter 1 : Introduction

This chapter provides the background issues of the studied research, including eco-design concerns at the early design stage and an overview of functional analysis. In practice, design information is difficult to capture at the conceptual design stage. Thus the methodology of this thesis is developed to integrate eco-design tools to support the conceptual design stage. In addition, the motivation and challenges of this research are reported, along with the research questions that illustrate the scope of this research. An overview of the methodology is also presented in this chapter. Finally, the thesis objectives and organization are presented.

1.1 Background

Environmental issues have become more significant in design practice. Environmentally conscious design (eco-design) aims to design a product that has less environmental impacts such as decreasing energy consumption, emissions and waste throughout the product life cycle. Such benefits can be better realized if environmental conditions are considered at the earlier phases of product development. On the other hand, many designs in practice are not developed from scratch but based on previous versions of similar designs (Otto and Wood, 2001). Thus, when engineers perform design activities at the early development stage, they should have some rough design information at hand. In this context, this study focuses on how to utilize the information of existing designs to support the conceptual design stage with the environmental concerns. Particularly, conceptual design refers to two types of design activities in this research: (1) design concept generation and (2) assessment of the design concepts.

There are several ways to minimize environmental impacts for a product. Undoubtedly, the highest opportunity occurs during the product design phases, as argued by some authors (Abele et al., 2005; Fiksel, 2009; Kutz, 2007; Ramani et al., 2010). Therefore, companies that develop new products must consider many factors related to the environmental impacts of their products (Fiksel, 2009) such as government regulations, consumer preferences, corporate environmental intentions. This will not only protect the environment but also reduce life cycle costs by decreasing raw material, energy use and avoiding the need for pollution control.

In response to the environmental concerns, researchers have extended the practice of quality function deployment (QFD) to cover the “voice of environment” (Devanathan et al., 2010; Kaebernick et al., 2003; Kuo et al., 2009; Zhang, 1999). The essence of QFD is to map between customer requirements and engineering metrics so that the improved engineering performance can actually enhance the satisfaction of customers. Figure 1.1 shows a typical QFD matrix structured in house of quality.

Several eco-design concepts refer to the need for new eco-design tools that efficiently reduce environmental impacts. These including the extension of green quality function deployment (G-QFD) to QFD II (Rathod et al., 2011), the presentation of functions flow via functional block diagrams (Stone and Wood, 2000), to guidelines for eco-design based on TRIZ theory to support design engineers (Sakao, 2007), to developing green products (Russo et al., 2014) and resolving conflicts between product functionality and environmental impacts (Fitzgerald et al., 2010). However, effective design modifications are not simple due to the design complexity of the engineered products.

As the target of this research is to address the environmental issues at the conceptual stage, the expected design element that should be considered at this stage is design function. Generally, design functions refer to the purposes of a product (i.e., what product supposed to do). To identify design functions, functional decomposition is often applied by breaking down the overall function into some smaller sub-functions. Several researchers have proposed different approaches to support functional modeling. For example, Pahl et al., (2007) and Stone and Wood, (2000) presented a functional basis to describe the feature set and the flow set of design linguistics for the construction of sub-functions. Lind, (1994) has commented that the understanding of design functions depends on the function flow which has been categorized into material, energy and signal flow.

A very minor design modification might lead to a decision of major design changes. Further, focusing on the responsible components for a modification may not be effective for generating new solution concepts. In this sense, suggestion of the practice of functional analysis (FA) basically provides a streamlined process from concept generation to concept assessment and selection to support eco-design. Such a design strategy will conserve energy and minimize waste. In eco-design, a tradeoff can be made by considering the environmental issues on the life cycle of a product.

While life-cycle assessment (LCA) is a common tool for environmental assessments of a product or system, it has been well recognized in engineering design that the traditional LCA procedure cannot be fully applied in conceptual design (Ashby, 2009; Ramani et al., 2010). One limitation is that the inventory analysis in LCA generally requires extensive product information, which is not quite available during the conceptual design stage. The general research inquiry of this thesis is how to incorporate the "rough" design information in the framework of LCA to provide some early environmental assessments of design concepts. Then, the early assessment results can be used to further improve the design concepts and support concept selection.

Fuzzy impact assessment has been used to capture the imprecise information in engineering design (Wood et al., 1992). In this research trapezoidal fuzzy numbers (TrFN) are used to represent "rough" design information for two reasons. Firstly, numerical intervals are common for engineers to understand the imprecise information (e.g., the use of tolerance). Fuzzy numbers in this sense are the generalization of intervals, and their numerical operations have been investigated extensively (Lee, 2006). Secondly, design estimation via TrFN requires (1) the range of typical values and (2) the upper and lower boundary values. Even though engineers should be familiar with the specification of these values, full specification is actually not required in practice. That is, TrFN can be flexibly changed to a triangular fuzzy number (TFN), an interval or even a crisp number without affecting the original formulations based on TrFN. The research motivation and challenges are described in the next sub-section.

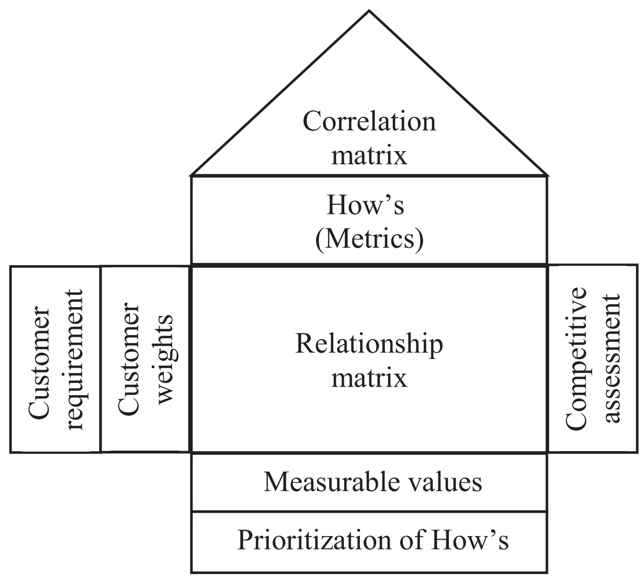


Figure 1.1. A typical QFD matrix in house of quality (Shillito, 1994)

1.2 Motivation and Challenges

Eco-design has promptly become a fundamental focus in design practice. A product designer is significantly required to determine the environmental impacts during the early design stage. To address the challenges of eco-design, a number of researchers in this field have devoted their efforts to integrate environmentally friendly products with engineering design methodologies. Toward the development of the eco-design based integration techniques, this issue is profoundly reviewed and discussed in Chapter 2. In this review the researchers provide a comprehensive summary of quality function deployment (QFD), functional analysis (FA), life cycle assessment (LCA), fuzzy assessment and eco-indicator method. In the literature review several aspects have been provided on green product design related issues and how designs can be integrated with such methodologies to mitigate environmental impacts.

The practice of LCA at the early stage of design is considered as a challenge. The challenge of considering the environmental issues during the early phase of design is that the detailed LCA information is not available at the early design phase (e.g., how much CO_2 is incurred from the existing design that is at this stage). Referring to Figure 1.2, the dotted line shows a shorter path leads to the implementation of LCA at the conceptual design stage. The LCA can be employed with rough design data at hand (e.g., estimate about 10-12 kg of CO_2 to be incurred). In addition, it has been commented that LCA generally requires significant time and resources to carry out (Ashby, 2009; González et al., 2002). In fact, since the typical practice of LCA relies on extensive information, it should not be applicable directly at the early product development stage due to incomplete design information.

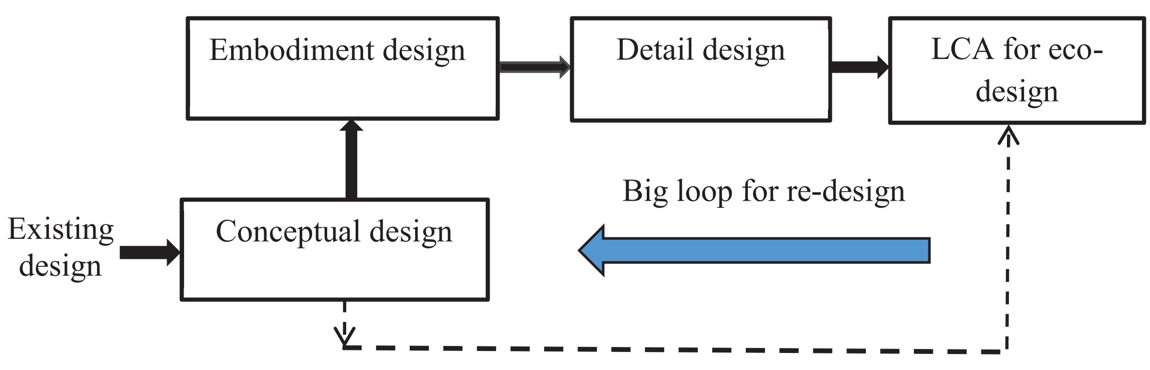


Figure 1.2. LCA and design process

To assess environmental impacts objectively, there are some standard indicators (e.g., Eco-indicator 99) in practice (Ashby, 2009; Fiksel, 2009). Each indicator can be viewed as a weight reflecting an environmental impact associated with a particular engineering quantity. At the conceptual design stage, the engineers may not have precise values of engineering quantities, which are only available after the detailed design stage. Yet, engineers should have some ideas to roughly estimate the values of these quantities. Hence the technical issue of this research is how to incorporate such "rough" design information for brief environmental assessments. In such a way, the engineers can estimate the environmental impacts of the design concepts.

From the above discussion the research has two new elements. Firstly, this research integrates QFD and FA to propose the conceptual design methodology for analyzing existing designs and exploring the opportunities for eco-design improvement. Secondly, this research explores the use of imprecise design information with eco-indicators to support early design environmental assessments and concept selection. While the relevant research objectives will be discussed in the next sub-section, the following questions guide the direction and scope of this research.

1. How can the information of an existing design be captured for QFD and FA for eco-design improvement?
2. How can design concepts be generated effectively with environmental considerations?
3. How can less precise information be incorporated in the early design stage?
4. How is it possible to perform and incorporate fuzzy impact assessments for concept selection?
5. Can the developed methodology be used in different applications to demonstrate the method's applicability?

1.3 Thesis Objectives

The primary goal of this research is to develop a method to support eco-design at the conceptual design stage. Conceptual design relies on two basic activities: concept generation and concept assessment. The developed method is expected to provide guidance for engineers to consider environmental concerns at the early design stage. To achieve this research goal, four specific research objectives are defined as follows:

1. Objective 1: To develop a suitable integration strategy that helps to satisfy the environmental requirements.
2. Objective 2: To develop a relational models to capture the relevant design information and facilitate eco-design improvement.
3. Objective 3: To develop a streamlined process from concept generation to concept assessment and selection to support eco-design improvement.
4. Objective 4: To demonstrate and validate the methodology via different case examples.

1.4 Methodology Overview

The eco-design method is mainly developed to achieve the objectives of this study. The method is built to reduce the environmental impact of an existing design. The basic strategy of this method is first to translate the environmental requirements to the functional description of the design. In such a way, the focus is on the corresponding functions to generate possible design solutions for improvement.

The procedure of this method starts by constructing the relational matrices of the existing design to capture the required design information. Through the practice of quality function deployment (QFD) and functional analysis (FA), engineers can analyze the design information and define the lists of requirements (R), metrics (M), components (C) and functions (F). In addition, the relational matrices are defined via *RM* (requirements and metrics), *MC* (metrics and components) and *FC* (functions and components) to capture the connections among the design elements of an existing design. The subset of functions that is responsible for eco-design becomes the output of this step.

Given the responsible functions, engineers can initiate the concept generation process using a morphological chart. In this chart, engineers are asked to propose various possible solutions to satisfy each of the functions. To synthesize a design concept, one possible solution is required for each function. For example, suppose that a design consists of two functions: f_1 and f_2, and each function has two possible solutions (or components), symbolically, f_1 with c_{1a} and c_{1b} and f_2 with c_{2a} and c_{2b}. To synthesize a design concept, one solution is needed for each function. Thus, there can be four possible design concepts as the outcome: $\{c_{1a}, c_{2a}\}$, $\{c_{1b}, c_{2a}\}$, $\{c_{1a}, c_{2b}\}$ and $\{c_{1b}, c_{2b}\}$. Notably, the possible number of design concepts can expand rapidly with the number of solutions for each function. Moreover, engineers should make their judgments to filter some promising design concepts.

After obtaining several design concepts from the previous step, these concepts are evaluated via a Pugh chart. Particularly, based on the metric evaluation, engineers can objectively assess the design concepts towards the satisfaction of requirements (*R*). Accordingly, engineers can evaluate how the new components can affect the related metrics and the satisfaction of relevant environmental requirements.

The evaluation step is further extended using fuzzy assessment method to evaluate the environmental impacts. At the stage of conceptual design, the engineers may not have precise values of the engineering quantities which should only be available after the stage of detailed design. Yet, the engineers should be able to anticipate the final designs and roughly estimate the values of these quantities. Fuzzy assessment is proposed to focus on capturing imprecise design information and incorporating such information with eco-indicators for decision making. The uncertain engineering quantities in this study are presented via trapezoidal fuzzy numbers (TrFN).

Finally, the proposed method is demonstrated via two different applications, home appliances and a diaphragm forming process. In addition, the method is described in detail in Chapters 3-6.

1.5 Thesis Organization

This thesis is intended to develop a methodology for eco-design at the early design stage. In this outline, the rest of this thesis is organized as follows: Chapter 2 provides a literature review of this research. In particular, the review comprises methods developed for eco-design, including quality function deployment (QFD) and life cycle assessment (LCA). Concept generation methods are also reviewed including functional analysis, TRIZ theory and a morphological chart. In addition, an assessment method, fuzzy uncertainty in LCA, is reviewed. Chapter 3 focuses on the development of relational matrices to integrate functional analysis (FA) in the domain of QFD to support the generation of design concepts of a product. The main purpose of this integration is to reduce environmental impacts systematically. Chapter 4 reports the analysis of the constructed relational matrices that lead to the generation and assessment of the newly designed concepts. This work is demonstrated via case examples. Chapter 5 presents another application, diaphragm forming process (DFP), to support the applicability of the proposed methodology. Chapter 6 discusses trapezoidal fuzzy numbers for eco-design assessment in the conceptual design stage. The method in this chapter is also demonstrated via case example (i.e., coffee maker). Chapter 7 provides a summary, contributions and future directions of this thesis.

Chapter 2 : Literature Review

This chapter provides a research review related to the developed methodologies in eco-design. Specifically, the review includes (1) methodical features of eco-design: this generally includes the attributes that have been considered to achieve eco-design improvement, (2) quality function deployment (QFD) and eco-design: this represents the capability of quality tools for achieving environmental requirements, (3) concept generation in eco-design: this includes functional analysis, morphological chart and TRIZ theory, (4) life cycle assessment (LCA) and eco-indicators: these include an overview of LCA and the eco-indicator methods, in particular, the Eco-indicator 99 in LCA, (5) LCA in conceptual design: this comprises LCA information at the early design stage and (6) fuzzy uncertainty in LCA.

2.1 Methodical Features of Eco-Design

Environmentally conscious design (eco-design) and design for the environment (DfE) have been a topic in engineering design and can be found in various textbooks (Fiksel, 2009; Otto and Wood, 2001). In this thesis, no distinction has been made between DfE and eco-design. This thesis mainly uses the term “eco-design”. In brief, eco-design is a view of product design with respect to environmental, health and safety objectives over the whole product and process life cycle (Fiksel, 2009). The early eco-design techniques are generally based on the experience of practitioners and are expressed as design guidelines (e.g., minimize the use of toxic materials). To examine eco-design in details, this section overviews three major features concerning eco-design methodology. In particular, these features are considered to characterize eco-design improvements: (1) capturing environmental requirements, (2) design concept generation and (3) assessment of the design concepts.

Firstly, in this study QFD is used to capture the environmental requirements. Among various quality tools, QFD has been widely recognized and developed to transform customer requirements into the design of products (Akao, 1990). QFD enables design information to be systematically structured to decrease the modification and the re-design time. One key feature of QFD is to utilize the "voice of customers" in product development for customer satisfaction. The QFD procedure is systematically described to build customer needs and engineering metrics into a structured matrix (Guinta and Praizler, 1993; Xie et al., 2003). Based on this idea, researchers have adapted QFD for eco-design by incorporating the "voice of environment" in the design planning process. While QFD can be a good tool to reflect the concerns of stakeholders (including customers and the environment), further efforts are required to integrate the results of QFD in the design process.

Secondly, while QFD is not often used for concept generation, design engineers sometimes employ functional analysis (FA) for this purpose. A function can be conceptually viewed as a conversion process among materials, energy and information (Stone and Wood, 2000). One representative functional description is the functional block diagram that describes the connection of different functions of a product. The functional description of a product is one important step towards design creativity and concept generation. For example, suppose that one function is to "heat up water". By focusing on this functional description, engineers can identify the necessary functional inputs (i.e., energy and cold water) and outputs (i.e., dissipated heat and hot water). Then, new design concepts can be generated by seeking for multiple ways to achieve this function in view of the conversion from the inputs to the outputs.

After generating the design concepts, the final step of eco-design improvement is concerned with the assessment and selection of design concepts. To select the promising design(s) for further product development, two assessment methods are used and developed in this thesis, and they are briefly discussed below.

- Pugh chart: A well-known quality tool for concept evaluation and selection. To promote the applicability of the developed method of this thesis, the Pugh chart is used by integrating the information from QFD for eco-design concept selection.
- Fuzzy assessment: A formal approach for addressing uncertainty information. A trapezoidal fuzzy number is used to capture the approximations of engineering quantities for assessing eco-design performance.

Notably, the research of eco-design methodology often focuses on one or two aspects discussed above (the works to be reviewed in next sections). In this thesis, it is concerned with the applicability of the developed method. Accordingly, it is intentional to employ quality tools (e.g., QFD and Pugh chart) and integrate them systematically for eco-design improvement. The applicability is demonstrated in this thesis via three case examples (i.e., coffee maker, hair dryer, forming machine).

Beyond applicability, this thesis investigates two formal subjects concerning eco-design. Firstly, while quality tools are often found in the literature such as design for six sigma or quality planning, functional analysis (FA) is the material of design theory and methodology. In the literature study, integrating quality tools with functional analysis for eco-design have not been formally investigated yet, and this becomes one formal subject of this thesis. The second formal subject is to employ the fuzzy numbers for analyzing the uncertainty of eco-design.

2.2 Quality Function Deployment (QFD) and Eco-Design

The quality function deployment (QFD) has been widely adapted among various quality tools for achieving eco-design requirements. The adaption of QFD has been addressed via three major methodical approaches. The first approach is termed “Green QFD”, which was initiated by Cristofari et al., (1996) and Zhang, (1999). In this approach, one key feature is to introduce the “Green House” (in addition to the House of Quality) to incorporate the life-cycle information such as life cycle assessment and life cycle costing in the QFD practice. Dong et al., (2003) have further advanced Green QFD using fuzzy multi-attribute utility theory for cost estimation.

The second approach is termed “Environmentally Conscious QFD” (ECQFD), which was found in the research of Kaebernick et al., (2003). Instead of building a new “house” in Green QFD, they added a new dimension (i.e., environmental metrics (EM)) over the House of Quality. This new dimension EM is mapped to customer and technical requirements respectively so that environmental concerns are part of the considerations among various requirements.

The third approach is termed “QFD for Environment” (QFDE), which was found in (Devanathan et al., 2010; Masui et al., 2003; Sakao, 2007). Conceptually, while Green QFD and ECQFD tend to focus on the assessment aspect (e.g., using Green House or EM), QFDE extends the “customer” concept by treating “environment” as one type of customer, resulting in a list of environmental voice of customer (VoC) in the practice of QFD.

In our view, the essence of QFD is about mapping customer requirements to the engineering domain so that what is needed to be improved in product development can be prioritized. In other words, the assessment aspect of QFD is beneficial only after the mapping of “customer” concerns is performed. Thus, the approach by QFDE is employed in this study since it is relatively simple and conceptually related to the essence of the “customer” in QFD. Also, this thesis will focus on the mapping process via matrices that are common in QFD.

Similar methods that integrate QFD and eco-design can also be found in Abele et al., (2005) and Fiksel, (2009). The detailed information of eco-design tools can be found in a review paper by

Ramani et al., (2010). Among these works, it is noticed that QFD is often used for "product planning" with respect to the mapping process as customer requirements → engineering metrics → product components. In other words, QFD is not primarily intended for "product design" in view of proposing new design concepts. To advance to the utility of QFD, the research of this thesis is intended to add design functions in this mapping process for supporting concept generation, and this idea has not been found in the current literature study.

2.3 Concept Generation in Eco-Design

As concept generation essentially is a "creative" process, its methodical procedures are not expected to behave like "algorithms" that produce definite outcomes. In literature of design theory and methodology, the well-known methods for concept generation include TRIZ (Theory of Inventive Problem Solving) and morphological chart. In TRIZ, the basic idea is to extract the design ideas from the published patents and use them for new design applications. In morphological chart, the "divide-and-conquer" approach is employed by first decomposing a design problem in terms of design functions. Then, engineers are asked to provide solutions for each design function for generating multiple design concepts (Eppinger and Ulrich, 1995; Pahl et al., 2007; Ullman, 2003).

As commented by Bocken et al., (2011), the generation of design concepts receives less attention (as compared to the assessment) in the context of eco-design. One classical approach is to employ the guidelines from Design for Environment in the conceptual design stage (Abele et al., 2005; Fiksel et al., 2009). Telenko and Seepersad, (2010) proposed a step-by-step method to develop eco-design guidelines in the conceptual design stage.

Besides the general eco-design guidelines, TRIZ has been employed as a systematic approach for generating innovative eco-design solutions (e.g., Fresner and Jantschgi, 2010; Kobayashi, 2006; Sakao, 2007). To facilitate TRIZ and other guidelines for non-experts, Russo et al., (2014) has developed the “iTree” method that provides specific guidance for various eco-design scenarios. Similar to the basic notion of TRIZ, Bohm et al., (2010) have used a design repository to generate and evaluate design concepts. Sakao, (2007) has combined TRIZ (theory of inventive problem solving) with QFD for eco-design.

In the review of eco-ideation, Bocken et al., (2011) have commented that a simple tool has the advantage for getting innovative concepts. Aligned with this viewpoint, this thesis employs the morphological chart for concept generation due to its simplicity, and it has been introduced in design textbooks (e.g., Otto and Wood, 2001; Pahl et al., 2007). In our view, the essence of the morphological chart for design innovation is twofold. Firstly, the “divide-and-conquer” approach is applied via product decomposition so that designers can focus on several smaller and simpler problems for new ideas. Secondly, the principle of “Form Follows Function” is used so that designers can focus on the “functions” (i.e., what the design wants to achieve) rather than the physical objects for problem solving.

Yet, the meaning of “function” can be easily confused in various methodical contexts. To clarify, “function” in this thesis is concerned with a kind of conversion (e.g., energy and matter) and is always described with an action verb (e.g., “generate” air flow). This definition is associated with a German design tradition (Pahl et al., 2007), from which the morphological chart is originated. In other words, it is different from functional requirements that have been described in some other methods (e.g., Du et al., (2013)). In addition, it should be noted that the classical framework of QFD does not directly include and map the design functions. As a new methodical element, this thesis highlights how to map from eco-design requirements to functions for supporting concept generation.

In sum, it is clear that the traditional practice of QFD does not include the information of design functions in the methodology. The lack of functional descriptions does not make QFD a proper tool for concept generation. One deliverable of this thesis is to show the integration of QFD and functional analysis (FA) to generate new concepts for eco-design improvement. An overview of the life cycle assessment is discussed in the next sub-section.

2.4 Life Cycle Assessment (LCA) and Eco-Indicators

Life Cycle Assessment (LCA) is well recognized for environmental design and management, and it has been documented through the International Organization for Standardization (ISO 14040 and ISO 14044) (Fiksel, 2009). Among various LCA stages, two of them are mostly studied in the LCA literature: inventory analysis and impact analysis. The duty of inventory analysis is mainly concerned with data collection, tracing the inputs (e.g., energy consumption) and outputs (e.g., wastes) associated with the products. In contrast, the duty of impact analysis is to quantify the impacts coming from these inputs and outputs towards the environment.

As LCA in general is a resource-intensive process, some checklist approaches have employed for prompt yet less precise assessments (Masui et al., 2003). When LCA is applied in the design process, one specific challenge is concerned with uncertainties due to incomplete / imprecise data from inventory analysis as well as uncertain consequences estimated in impact analysis (Ramanujan et al., 2011; Rebitzer et al., 2004; Suiran et al., 2001).

To address the challenge of using LCA in engineering design, Eco-indicator 99 is selected as the dataset to assess environmental performance of a product in this thesis. The key reason of this selection is that Eco-indicator 99 is specifically prepared by well-known LCA organizations for product designers who do not have in-depth knowledge in environmental science (Goedkoop and

Spriensma, 2001). Additionally, Eco-indicator 99 (or 95) has been introduced in design textbooks for environmental assessment (e.g., Otto and Wood, 2001).

From here in this thesis, “eco-indicators” are referred to the assessment information based on Eco-indicator 99. Intuitively, eco-indicators can be viewed as “environmental price tags” attached to certain materials and processes. For example, the eco-indicator value of injection moulding of polystyrene (PS) is equal to 21 milli-points (mPt) per kg (of PS) where mPt is dimensionless. This dimensionless unit is obtained by some normalization and weighting procedures conducted by LCA experts in advance. Then, the environmental impacts of a product can be calculated by multiplying eco-indicators with the actual quantities used in the product. Higher eco-indicator values imply stronger environmental impacts.

As commonly observed in environmental research, the use of “standard” eco-indicators is not without controversy. To elaborate, Eco-indicator 99 is known as an end-point indicator that has assumed the weights among three ultimate areas of protection (i.e., resources, eco-system quality and human health). In the environmental analysis, each area of protection is associated with multiple damage models (e.g., how the greenhouse gas affects the climate that eventually influences human health). In this context, the controversy can come from the weightings concerning the areas of protection and the choice of damages models.

In contrast to Eco-indicator 99, the mid-point indicators have also been used in LCA (Bare and Gloria, 2008), and they basically leave the weightings of “areas of protection” to be determined by users. Following the effort of Eco-indicator 99, ReCiPe (Goedkoop et al., 2009) has been developed to harmonize both mid-point and end-point indicators. Though various datasets have been available (e.g., Ecoinvent and ReCiPe), it is still a difficult task for design engineers to perform such analysis at the early design stage given various design options at hand.

Towards this end, the methodology of this thesis simply assumes the availability of eco-indicators in the decision process, and Eco-indicator 99 is just one example that can be used for demonstration. Nevertheless, the proposed methodology does not restrict designers from developing their own sets of eco-indicators for a particular project. Arguably, no matter using Eco-indicator 99 or in-house indicators, it is considered that the eco-indicators should be available at some point in the assessment process, even though the calculation procedures and terminologies can be different from one another.

2.5 LCA in Conceptual Design

As mentioned above, using LCA in the design process is not trivial due to the lack of design details especially in the early design stage (Millet et al., 2007). To deal with incomplete product information, Graedel et al., (1995) proposed a streamlined LCA that used a 5-by-5 matrix to capture five environmental concerns with respect to five life-cycle stages. Each matrix entry represents one specific context of environmental impacts, which can be assessed by some rating scores. In this case, though the rating system is arguably semi-quantitative, it somehow caters the situation of incomplete product information.

In eco-design research, various efforts have been reported to integrate LCA in the design process. Linton, (2012) and Chen et al., (2002) have adapted the techniques of Data Envelopment Analysis (DEA) to examine the ratio of benefits (e.g., engineering performance) to environmental impacts for assessing the "environmental efficiency" of design products. Focusing on system redesign, Harper and Thurston, (2008) used multi-attribute utility analysis to examine the trade-offs between system cost and environmental impacts over a long period of time. Kishita et al., (2010) quantified the checklist practice by assigning weights to environmental requirements based on CO_2

emissions. Bocken et al., (2011) developed an eco-ideation tool to facilitate the generation of radical product ideas to reduce greenhouse gas emissions for consumer goods.

Furthermore, several research works have utilized the LCA information of existing design to support LCA in the early design stage. By using such information, Telenko and Seepersad, (2010) identified the environmental priorities and generated guidelines for environmental design. Devanathan et al., (2010) developed the function-impact method that supports engineers to relate design functions with environmental impacts for concept generation. Bohm et al., (2010) applied LCA to the virtual design models in the design repository to support environmental assessments during conceptual design. Kobayashi, (2006) presented a systematic approach based on life cycle planning to support idea generation using TRIZ, design uncertainty and eco-efficiency indicator.

In the proposed method, two methodical features are common to the above reviewed works. Firstly, the LCA information of existing design is utilized. The workflow of the design example basically follows the reverse engineering concept in Otto and Wood, (2001) and Telenko and Seepersad, (2010). Secondly, the eco-indicators are applied for quantifying and aggregating various types of environmental impacts. Tackling the challenges of using LCA in the early design stage, the new element of the proposed method is to treat incomplete product information as one kind of design uncertainty in eco-design assessments. Based on the information of existing design, engineers are expected to have certain expertise to estimate the ranges of some engineering quantities (e.g., weights of some new components) for new design concepts. The next sub-section will review some techniques to handle uncertainties in LCA.

2.6 Fuzzy Uncertainty in LCA

As uncertainties are common in design, uncertainty treatments (mainly based on fuzzy sets) that have been proposed and discussed in the context of LCA are reviewed. The issues of uncertainty in

LCA are indeed extensive (Finnveden et al., 2009; Lloyd and Ries, 2007). Generally speaking, the uncertainty of LCA can be classified into two types: data uncertainty and model uncertainty. Data uncertainty is concerned with the quality of the data obtained from inventory analysis, while model uncertainty is generally concerned with the assumptions made in impact assessments (e.g., system boundary). The specific focus of this research belongs to the uncertainty of design data that is used in LCA (i.e., data uncertainty).

While some LCA software tools (e.g., SimaPro) have incorporated Monte Carlo simulations to analyze the variability of input data, fuzzy set theory has been chosen as the basic approach to handle design uncertainty. The reason is that design uncertainty at the conceptual stage is more relevant to the judgments by engineers rather than stochastic imprecision (Wood et al., 1992). Thus, this sub-section will focus on the application of fuzzy set theory in LCA.

The methodical approaches based on fuzzy set theory in LCA can be generally classified into two streams: fuzzy linguistics and fuzzy quantities. In fuzzy linguistics, fuzzy sets are applied to quantify linguistic variables that are used for subjective judgments. Afrinaldi and Zhang, (2014); Boclin and de Mello, (2006); González et al., (2002) focused on developing fuzzy inference rules for overall environmental assessments. Bovea and Wang, (2003) and Kuo et al., (2009) applied fuzzy linguistic data in the framework of quality function deployment (QFD) for the practice of LCA. Güereca et al., (2007) and Liu and Lai, (2009) used fuzzy linguistic variables to formalize the valuation process from empirical data to expert judgments in LCA. Benetto et al., (2008) and Kuo et al., (2006) have studied fuzzy judgments by designers to perform multi-criteria analysis in LCA.

In contrast, some research works have applied fuzzy numbers to capture the uncertainty associated with LCA inventory quantities (Weckenmann and Schwan, 2001). Tan, (2008) applied triangular fuzzy numbers to incorporate uncertainty in the matrix-based life-cycle inventory (LCI) analysis. Reza et al., (2013) used fuzzy numbers to quantify "Unit Emergy Values" in environmental assessments. This thesis aligns with this research direction of fuzzy quantities to capture the uncertain design information in LCA. Besides the eco-design context, the technical contribution in this thesis based on fuzzy assessment is the development of the pessimistic and optimistic values associated with a trapezoidal fuzzy number (TrFN) for decision analysis. Also, the ranking methods have been developed by utilizing fuzzy information for eco-design analysis.

2.7 Summary

Developing methods to reduce environmental impacts has become an essential and uttermost necessity, especially when data and information are imprecise. This chapter introduced an overview of the utilized tools and techniques for eco-design improvement. Based on the existing research, there are not many methodologies associated with concept generation for the purpose of solving eco-design problems. In particular, functional descriptions are not integrated with QFD. This does not make QFD an appropriate tool for design concept generation. In addition, LCA has challenges as a result of lacking information in the early design stage. In this case, fuzzy impact assessment is applied to capture the uncertain design information in LCA for supporting decision making. In this thesis, a new eco-design approach for how to address environmental issues is proposed in a systematic procedure. Chapters 3-6 show the developed method for the described eco-design problem and demonstrate the applications for eco-design improvement.

Chapter 3 : Model Development using Relational Matrices

In this chapter, quality function deployment (QFD) and functional analysis (FA) are systematically integrated to reduce environmental impacts at the conceptual design stage. While QFD provides a framework to reflect the "voice of environment" (VoE) in the design planning and evaluations, FA focuses on the functional description of the design to support the generation of design concepts. Three relational matrices, which are *RM* (requirements and metrics), *MC* (metrics and components) and *FC* (functions and components) are constructed to explicitly capture the linkage information among the design elements of an existing design. The obtained results from this study are based on two case examples, a coffee maker and hair dryer.

3.1 Design Elements

In this work four specific design elements are identified according to the context of QFD and FA, and they are identified as follows.

- Requirements: These include customer and environmental requirements according to the context of QFD. These reflect the fundamental concerns related to the modification of existing designs. Such requirements of a coffee maker include heat quickly, less energy consumption and less material usage. In the practice of QFD, suppose that engineers have identified k requirements (R) to reflect the needs of customers and the environment. Let $R = \{r_1, r_2, \ldots, r_i, \ldots, r_k\}$ be the set of k requirements that cover both the "voice of customers" and the "voice of environment".
- Metrics: These correspond to engineering characteristics in QFD, reflecting the actual performance of a design via specific engineering measures (e.g., weight and energy). The

metric is denoted as (M). Let M = $\{m_1, m_2, \ldots m_j, \ldots, m_l\}$ be the set of l metrics that can be used to measure the engineering properties of a design.

- Functions: These describe what the design is expected to accomplish. They are usually expressed in terms of "verb-object" pairs to describe the desired actions as the functions (Stone and Wood, 2000). Such functions include (e.g., heat water and warm brewed coffee). In this work, the function is denoted as (F). Let $F = \{f_1, f_2, \ldots, f_i, \ldots, f_q\}$ be the set of q functions of a product.
- Components: These capture the design parts or solutions to fulfill the functions of the design. Examples include heater plate, housing, etc. Note that the component is denoted as (C). Let $C = \{c_1, c_2, \ldots c_j, \ldots, c_p\}$ be the set of p components.

Further to the description of the design elements, it is significant to present the QFD and the FA analysis domains, which are required to be integrated for the purpose of reducing the environmental impacts.

3.2 Domain of QFD

In the practice of quality function deployment (QFD), the mapping between requirements and metrics is essential so that the improvement of engineering characteristics (i.e., metrics) can actually enhance the satisfaction of customers. Then, a relational model can be built using matrix representation to reflect the mapping between requirements (i.e., R) and metrics (i.e., M). This QFD practise is termed QFD I. Some QFD experts have also suggested the extension to map between metrics and components (termed as QFD II) to connect the design solutions with the proper engineering measures (Hauser and Clausing, 1988; Sakao, 2007). Following the practice of QFD II, engineers can make a further mapping from metrics to components (i.e., C). In this sense, the practice of QFD is basically suggested to provide the mapping from requirements to metrics to components.

In sum, through the practice of QFD, two matrix-based relational models, which are *RM* and *MC* matrices can be obtained.

3.2.1 *RM* Matrix Based on QFD I

After identifying the requirements (*R*) and the engineering metrics (*M*), the relational matrix *RM* is built to capture how strong a metric is associated with requirements. In the example of a hair dryer, the requirement (r_1) "less drying time" is strongly associated with the metric (m_1) "amount of energy" since higher amount of energy can directly lead to shorter drying time. Then, designers will focus on the most important requirements and examine the corresponding metrics for engineering measures. The *RM* mapping refers to practice of QFD I, which is the first mapping in QFD from customer requirements to engineering metrics.

Let $RM = [rm_{ij}]$, where rm_{ij} denote the relational strength between the *i*th requirement and the *j*th metric. The ranges of the subscripts are $1 \leq i \leq k$ and $1 \leq j \leq l$. In this formulation, *RM* is an *k*-by-*l* matrix, and rm_{ij} indicates the relevance of the *j*th metric (m_j) towards the satisfaction of the *ith* requirement (r_i). We have $rm_{ij} = 0$ if the requirement and metric have no relation. The formulation of the *RM* relational matrix is given as follows.

$$RM = \begin{bmatrix} rm_{11} & rm_{12} & \cdots & rm_{1l} \\ rm_{21} & rm_{22} & \cdots & rm_{2l} \\ \vdots & \vdots & \ddots & \vdots \\ rm_{k1} & rm_{k2} & \cdots & rm_{kl} \end{bmatrix} \tag{3.1}$$

The scale "1, 3, 9" is used to quantify a mapping relation (namely, QFD ratings for convenient). Particularly, 1, 3 and 9 are referred to weak, medium and strong relations, respectively. Interested readers may refer to Masui et al., (2003) and Rathod et al., (2011) for the detailed explanation and construction of *RM* matrix in the context of QFD I.

Figure 3.1 illustrates the *RM* matrix and the graphical mapping based on the subsets of requirements (*R*) and metrics (*M*) of the hair dryer example. For example, the relationship between the requirement (i.e., less drying time (r_1)) and the metric (i.e., the amount of energy (m_1)) shows strong relationship, that high relevancy of the amount of energy (m_1) used for achieving the (r_1) less drying time. The proposed process enables the engineering metric (i.e., *M*) to measure the efficiency by which the required quality (i.e., *R*) can be satisfied.

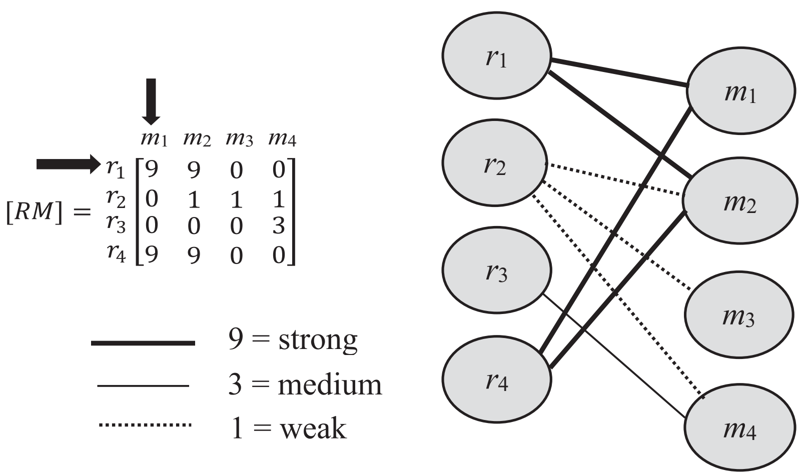


Figure 3.1. Mapping of *R* and *M*

3.2.2 *MC* Matrix Based on QFD II

The relational matrix *MC* captures the mapping between metrics (*M*) and components (*C*) according to the practice of QFD II. The purpose of this mapping is to connect design solutions (i.e., physical components) with the suitable engineering measures. For example, the heating element (c_3) as one component of a hair dryer can be assessed with one metric "m_1: amount of energy".

Let $MC = [mc_{ij}]$, where mc_{ij} denotes the relational strength between the ith metric and the jth components, and the ranges of the subscripts are $1 \leq i \leq l$ and $1 \leq j \leq p$. The same scheme of 1, 3 and 9 as presented in QFD I is used for quantifying the strength of relations. Interested readers may refer to Masui et al., (2003) and Sakao, (2007) for further details of constructing the *MC* matrix in the context of QFD II. The formulation of the *MC* relational matrix is given as follows.

$$[MC] = \begin{bmatrix} mc_{11} & mc_{12} & \cdots & mc_{1p} \\ mc_{21} & mc_{22} & \cdots & mc_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ mc_{l1} & mc_{l2} & \cdots & mc_{lp} \end{bmatrix} \tag{3.2}$$

Figure 3.2 illustrates the *MC* matrix and the graphical mapping based on the subsets of metrics (*M*) and components (*C*) of the hair dryer example. For instance, it is noted that the air flow (m_2) depends on two components: motor (c_1) and fan (c_2). Therefore, the improvement of m_2 will need the modifications of c_1 and/or c_2 during the eco-design process.

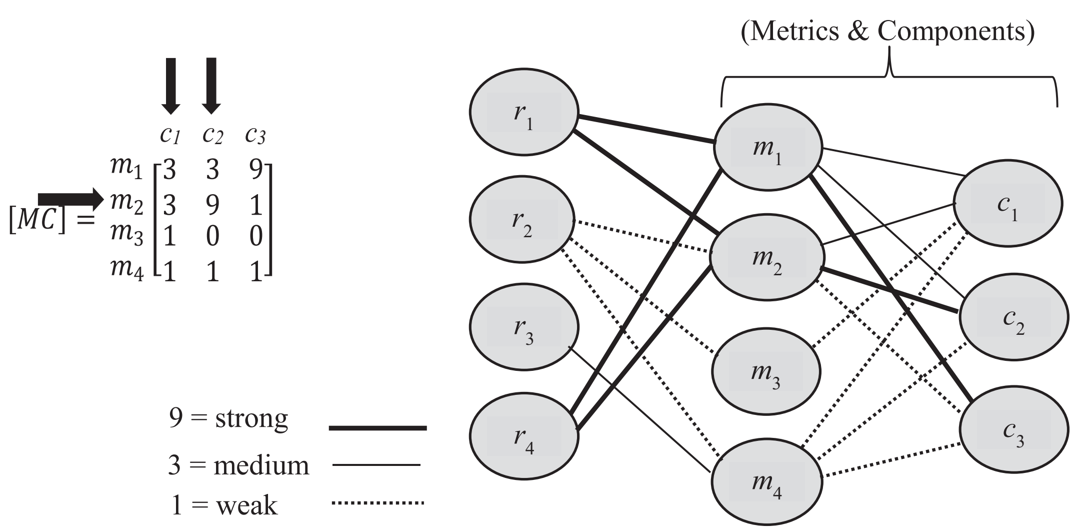


Figure 3.2. Mapping of *M* and *C*

3.3 Domain of Functional Analysis

In the practice of functional analysis (FA), one key procedure is to model the connections between various design functions in terms of material, energy and information flows. A function can be conceptually viewed as a conversion process among materials, energy and information. For example, suppose that one function is to "heat up water". Then, the inputs of this function is energy and cold water (as one material), and the outputs after the conversion can be dissipated heat and hot water. Stone and Wood, (2000) organized and represented the descriptions and flows of these functions via functional block diagram.

3.3.1 Functional Descriptions

The functional description of a product is one important step towards design creativity and analysis. For example, the function "heat up water" does not imply how this function can be achieved. By focusing on this functional description, engineers can be unlocked from existing solutions and explore the possible ways to achieve this function (e.g., energy source from fire, electricity or sun). This approach is used to simplify the complexity of a design. Designers can have different visions of solving design problems.

Functional decomposition can present functional descriptions in a hierarchy to simplify the decision making of a complex design. The aim of the decomposition is to break down functions into sub-functions to show their interactions in different levels of a product or a system (Kirschman and Fadel, 1998). Figure 3.3 shows a general hierarchy of system design relations in the horizontal and vertical interactions (Shupe et al., 1987). In our study, a hierarchy decomposition based design functions is employed for the purpose of functional analysis.

In addition, components are suggested to fulfil the functions, and it is similar to the practice of mapping functional requirements and design parameters in axiomatic design which was developed by Suh, (2001). In fact, morphological chart is based on the functional descriptions to combine various components (or solutions) for design concept generation (Otto and Wood, 2001). In this sense, the practice of FA basically provides the mapping from functions to components. Thus, the *FC* matrix can then be obtained too.

Notably, the traditional practice of QFD does not include the information of functions in the methodology. The lack of functional descriptions makes QFD not exactly a proper tool for design concept generation. One deliverable of this study is to show the integration of QFD and FA to generate new concepts for eco-design.

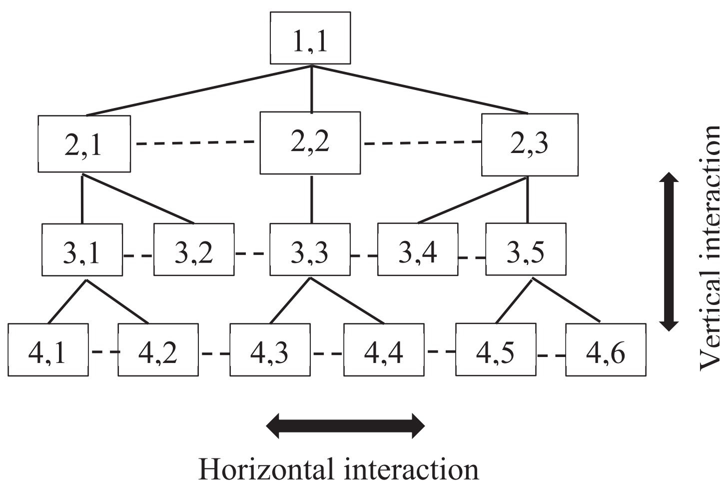


Figure 3.3. General hierarchical systems (Shupe et al., 1987)

3.3.2 *FC* Matrix Based on Functional Decomposition

A function has been viewed as a flow process with the inputs and outputs of materials, energy and information, and it remains one key notion for concept generation (Stone and Wood, 2000). For example, suppose that one function of a kettle is to “heat up water”. After specifying the inputs and the outputs of this function, engineers can brainstorm the possible ideas for the conversion between inputs and outputs. This “Form Follows Function” principle is operated behind the morphological chart. Then, the *FC* matrix is constructed to reflect what components are used to satisfy specific functions.

Let $FC = [fc_{ji}]$, where fc_{ji} denotes the relational strength between the ith component and the jth function, and the ranges of the subscripts are $1 \leq i \leq p$ and $1 \leq j \leq q$. The same scheme of 1, 3 and 9 as presented in QFD I and QFD II is used for quantifying the strength of relations. Interested readers may refer to Devanathan et al., (2010) for further details of the *FC* matrix. The formulation of the *FC* relational matrix is given as follows.

$$[FC] = \begin{bmatrix} fc_{11} & fc_{12} & \cdots & fc_{1p} \\ fc_{21} & fc_{22} & \cdots & fc_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ fc_{q1} & fc_{q2} & \cdots & fc_{qp} \end{bmatrix} \tag{3.3}$$

Figure 3.4 illustrates the *FC* matrix and the graphical mapping based on the subsets of functions (*F*) and components (*C*) of the hair dryer example. The purpose of this mapping is to connect design solutions with design functions. By this way, environmental impacts can be exposed in view of functions, thus the suitable components that contribute to decrease the impacts can then be selected. For instance, when engineers seeks for the changes of the heating element (c_3), this matrix indicates that such changes can strongly influence f_2 (i.e., heat air flow) as well as slightly affect f_1 (i.e., generate air flow).

$$FC = \begin{bmatrix} 9 & 9 & 1 \\ 3 & 0 & 9 \\ 3 & 0 & 0 \\ 0 & 3 & 0 \end{bmatrix}$$

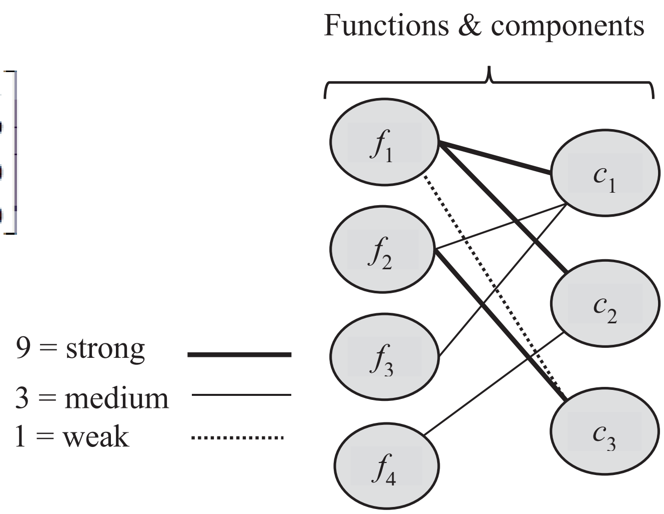


Figure 3.4. Mapping of *F* and *C*

3.4 Remarks on Relational Matrices

As the scheme of "1, 3, 9" is used for quantifying the mapping strengths in *RM*, *MC* and *FC*, it is acknowledged that such quantitative values cannot be very precise in practice (Yang, 2011). Notably, the "1, 3, 9" scheme has been commonly applied in various studies and reported in the literature of QFD (Devanathan et al., 2010). Though it may not be theoretically attractive, it is argued that the "1, 3, 9" scheme has been well applied in practice due to its simplicity.

Besides, the traditional practice of QFD often incorporates other pieces of information under the House of Quality, such as the customer weights, trade off analysis and the competitive benchmarks (Akao, 1990). Such information is not included in our extended method for two reasons. Firstly, this study assumes that the eco-design problem is initiated by some environmental VoC (e.g., less energy consumptions). Thus, it is not required to rank the VoC again based on customer weights. Secondly, by the view of authors, the core essence of QFD is its mapping process that deploys the customer needs systematically in product development. Thus, the methodical development of this thesis focuses on such mapping process without including too much information about performance assessment.

As eco-design in this study is based on the improvement of the existing design, the development of relational matrices can be viewed as the process of capturing the information of the existing design. Based on the obtained relational matrices, one key step contributed in this thesis is to link between requirements and functions systematically. Then, the environmental VoC can be mapped to the product's functions for concept generation using the morphological chart. This step will be discussed in the next chapter.

3.5 Procedure for Developing Relational Matrices

In the development of relational matrices, the starting point is the existing design. Then, the subsequent steps still rely on the experience of engineers. The value of relational matrices is to provide some kind of templates for engineers to collect the relevant design information. Nevertheless, a brief procedure is provided here to describe the general steps used in this research to develop the relational matrices.

- Step 1: Product Decomposition

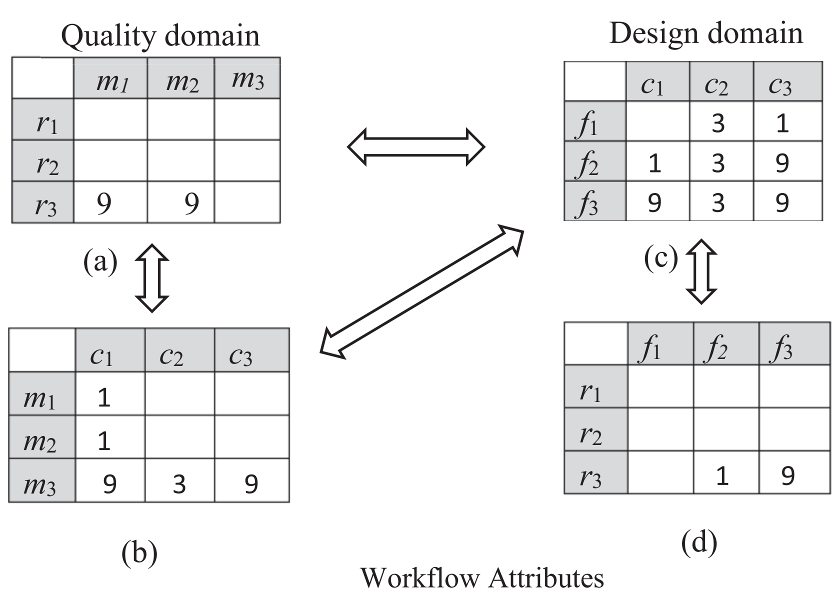
  This technique is applied to disassemble a product to identify its component parts and discover their functions. This approach is similar to the concept of reverse engineering in product design and development. Based on the determined components, the Bill of Materials (BOM) list can be determined includes the weight, types of materials and manufacturing method. Interested readers may refer to Otto and Wood, (2001) for further details about product decomposition.

- Step 2: Identification of Design Elements

  There are four types of design elements: requirements (*R*), metrics (*M*), functions (*F*) and components (*C*). The components can be listed from the result of product decomposition. The product's functions are explored by checking its components. For example, the component "reheat plate" in a coffee maker can lead to the function "keep coffee warm". The requirements and metrics are identified based on the understanding of customer needs and eco-design targets. A systematic method for obtaining customer requirements can be found in Eppinger and Ulrich, (1995).

- Step 3: Assignment of Matrix Entries

  The basic idea of matrix entries is to capture the association strength between two types of design elements (e.g., rm_{ij} → how relevant of m_j to assess the satisfaction of r_i). In the literature of QFD and FA, the matrix entries are usually assessed by point scale (e.g., the 9-point scale). In our model of relational matrices, three relational matrices *RM*, *MC* and *FC* are obtained through the practice of QFD and functional analysis (FA). Afterwards, the *RF* matrix is derived based on matrix multiplications to evaluate the eco-design requirements in view of functions. Figure 3.5 illustrates the relational matrices workflow.



(a): *RM* (requirements and metrics) matrix
(b): *MC* (metrics and components) matrix
(c): *FC* (functions and components) matrix
(d): *RF* is derived matrix

Figure 3.5. Relational matrices workflow

3.6 Example: Coffee Maker

This section aims to demonstrate the proposed eco-design integration step using a household coffee maker as an example. Figure 3.6 shows the parts of the coffee maker after the disassembly. The basic research question is how to systematically redesign this product for reducing environmental impacts. The developed model is primarily demonstrated and the rest of the procedure is shown in the next chapter.

Figure 3.6. Disassembly of the coffee maker

The coffee maker is first analyzed in view of requirements (*R*), metrics (*M*), functions (*F*) and components (*C*). This information is assumed available since it is an existing design, and the engineers of the company should be able to access such information. In this study, the lists of requirements, metrics, functions and components are defined and shown in Table 3.1, which the labels of these design elements are also defined (e.g., r_1, m_1, etc.).

Afterwards, the relational matrices *RM*, *MC* and *FC* of the coffee maker are constructed and provided from the formulated Equations (3.1) to (3.3). These matrices have three levels of relational strengths: weak (= 1), medium (= 3) and strong (= 9), and these levels are set based on the traditional practice in QFD. The matrix entries are left blank for the absence of relationship. The coffee maker improvement can be achieved in view of energy consumption reduction. Further analysis of the constructed relational matrices is accomplished in the next chapter.

Table 3.1. List of requirements, metrics, functions and components

Requirements (R)	Metrics (M)	Functions (F)	Components (C)
r_1: Safe operation r_2: Comfortable to hold r_3: Heat quickly r_4: High filtering efficiency r_5: Load capacity r_6: Durable r_7: Low cost r_8: Automatic shut off r_9: Less material usage r_{10}: Less energy consumption r_{11}: Light weight r_{12}: Easy to disassemble r_{13}: Reheat option	m_1: Amount of energy m_2: Thermal distribution m_3: Filter efficiency m_4: Lifespan m_5: Toxicity of materials m_6: Weight m_7: Types of materials m_8: Glass volume m_9: Noise and vibration m_{10}: Reheat temperature	f_1: Receive coffee materials f_2: Mix hot water and powder f_3: Filter out coffee powder f_4: Facilitate materials removal f_5: Distribute electricity f_6: Heat water f_7: Warm brewed coffee f_8: Dissipate heat f_9: Distribute weight	c_1: Carafe (thermo flask) c_2: Filter body c_3: Temporary filter c_4: Top housing c_5: Base housing c_6: Heater cover plate c_7: Heater plate c_8: Base (hot plate) c_9: Water spreader

$$[RM] = \begin{bmatrix} 0 & 0 & 0 & 3 & 3 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 9 & 0 & 3 & 0 & 0 \\ 9 & 9 & 0 & 1 & 0 & 0 & 9 & 3 & 0 & 9 \\ 0 & 0 & 9 & 3 & 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 0 & 0 & 9 & 0 & 1 \\ 0 & 0 & 0 & 9 & 0 & 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 3 & 0 \\ 9 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 3 & 9 & 9 & 3 & 0 & 0 & 0 \\ 9 & 9 & 0 & 0 & 0 & 0 & 9 & 3 & 0 & 9 \\ 0 & 0 & 0 & 0 & 0 & 9 & 9 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 \end{bmatrix}$$

$$[MC] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 3 & 9 & 9 & 0 \\ 1 & 0 & 0 & 0 & 0 & 3 & 9 & 9 & 0 \\ 9 & 3 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 3 & 1 & 0 & 3 & 3 & 1 & 1 & 0 & 0 \\ 9 & 1 & 1 & 3 & 3 & 1 & 3 & 3 & 0 \\ 9 & 3 & 3 & 3 & 3 & 1 & 3 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 9 & 9 & 0 \end{bmatrix}$$

$$[FC] = \begin{bmatrix} 0 & 3 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 3 & 9 & 0 & 0 & 0 & 3 & 0 & 9 \\ 9 & 3 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9 & 3 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 9 & 9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 9 & 3 & 0 \\ 3 & 0 & 0 & 0 & 0 & 3 & 9 & 9 & 0 \\ 3 & 1 & 0 & 1 & 0 & 0 & 3 & 3 & 0 \\ 9 & 3 & 0 & 9 & 9 & 3 & 3 & 1 & 1 \end{bmatrix}$$

3.7 Example: Hair Dryer

In this study, a consumer-grade hair dryer is selected as a second example for the demonstration of the proposed method. Figure 3.7 shows the disassembly of the selected hair dryer. Given this hair dryer at hand, the basic eco-design question is how to redesign this product for reducing environmental impacts. The proposed method in this thesis is intended to achieve this eco-design task in a systematic manner.

To better understand the existing product, two types of decomposition are carried out in this study, product and functional decomposition. In product decomposition, it is intended to identify and weigh some basic parts of the hair dryer. The output is the basic Bill of Materials (BOM), which is recorded in Table 3.2. By functional decomposition, it is to identify the sub-functions that support the main function of a hair dryer (i.e., to dry hair). Figure 3.8 shows the result that indicates the hierarchical relations of the product's sub-functions.

Notably, when the company plans to redesign their own product, they should have more information than what being captured in this BOM and product sub-functions. Thus, these two types of decomposition are only applied as optional steps for gathering the design information, and their working procedures are not discussed here. Interested readers may refer to Stone and Wood, (2000) for more information about product and functional decomposition.

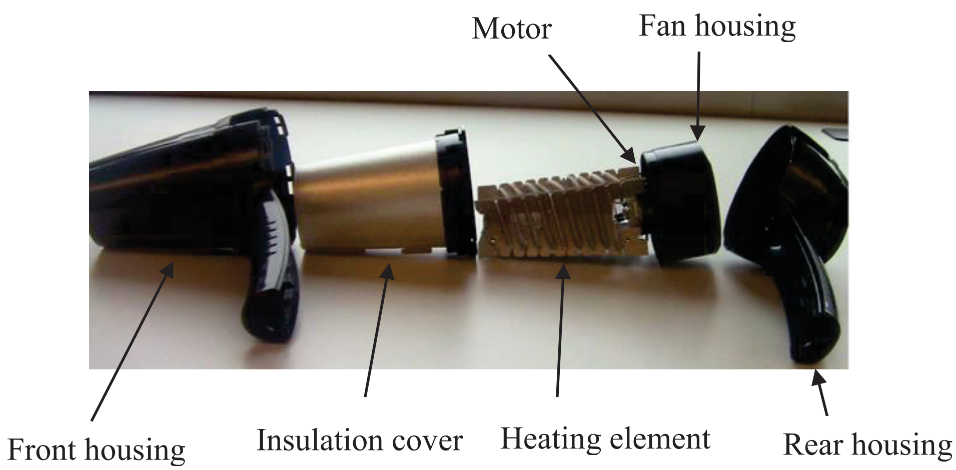


Figure 3.7. Disassembly of the hair dryer

Table 3.2. Bill of materials of the hair dryer

Parts	Materials	Weight	Manufacturing method
Motor	Steel, plastic and copper	63.2g	Rolling and forging etc.
Fan	Plastic	4.1g	Wire drawing
Heating element and fixtures	Steel	43.15g	Wire drawing
Front housing	Plastic	86.13g	Injection molding
Rare housing	Plastic	37.81g	Injection molding
Insulation cover	Paper carton	7.51g	Forming sheets
Fan housing	Plastic	17.45g	Injection molding
Power switch	Plastic	3.83g	Injection molding
Heating switch	Plastic	7.34g	Injection molding
Cord	Plastic and copper	103.6g	Wire drawing

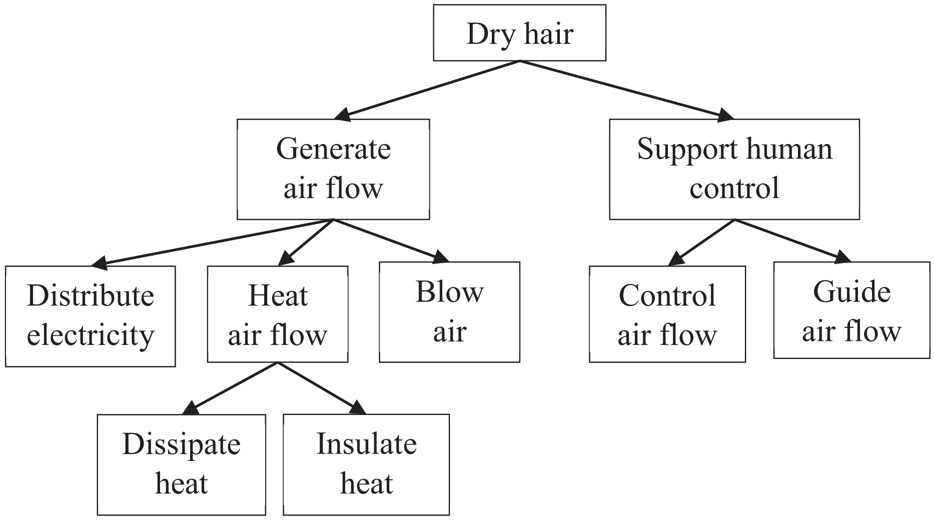


Figure 3.8. Functional decomposition of the hair dryer

In this work, the information of the hair dryer concerning requirements (*R*), metrics (*M*), functions (*F*) and components (*C*) has been listed in Table 3.3. The information of functions and components can be obtained from the functional decomposition and the BOM, respectively discussed in Section 3.2. In contrast, the information of requirements and metrics can be obtained via the practice of QFD. Based on the practice of QFD and functional analysis, three relational matrices of the hair dryer, *RM*, *MC* and *FC*, are determined and provided from the formulated Equations (3.1) to (3.3).

$$[RM] = \begin{bmatrix} 9 & 9 & 0 & 0 & 1 & 0 & 1 & 3 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 9 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 & 1 & 3 & 1 & 3 \\ 9 & 9 & 0 & 0 & 3 & 0 & 3 & 3 & 0 & 0 \\ 3 & 0 & 9 & 0 & 0 & 9 & 3 & 0 & 0 & 3 \\ 0 & 0 & 1 & 0 & 0 & 1 & 3 & 0 & 3 & 3 \\ 0 & 0 & 9 & 0 & 0 & 9 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 1 & 0 & 1 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 3 & 0 & 9 & 0 & 0 & 0 \end{bmatrix}$$

$$[MC] = \begin{bmatrix} 3 & 3 & 9 & 1 & 3 & 3 & 3 & 3 \\ 3 & 9 & 1 & 1 & 3 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 3 & 3 & 9 & 0 & 0 & 3 & 1 & 3 \\ 9 & 3 & 1 & 9 & 3 & 1 & 1 & 1 \\ 0 & 0 & 3 & 1 & 1 & 1 & 0 & 0 \\ 1 & 3 & 9 & 0 & 0 & 3 & 1 & 1 \\ 9 & 3 & 0 & 9 & 3 & 0 & 0 & 0 \\ 3 & 0 & 1 & 3 & 1 & 3 & 0 & 0 \end{bmatrix}$$

$$[FC] = \begin{bmatrix} 9 & 9 & 1 & 0 & 0 & 1 & 1 & 3 \\ 3 & 0 & 9 & 0 & 0 & 3 & 1 & 3 \\ 3 & 0 & 0 & 1 & 3 & 0 & 0 & 3 \\ 0 & 3 & 0 & 3 & 3 & 0 & 0 & 0 \\ 0 & 3 & 1 & 3 & 3 & 3 & 0 & 0 \\ 9 & 0 & 1 & 0 & 0 & 3 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 3 & 9 & 0 \\ 0 & 0 & 9 & 0 & 0 & 1 & 1 & 3 \\ 0 & 0 & 0 & 0 & 0 & 1 & 3 & 3 \end{bmatrix}$$

Table 3.3. List of requirements, metrics, functions and components of the hair dryer

Requirements (*R*)	Metrics (*M*)	Functions (*F*)	Components (*C*)
r_1: Less drying time r_2: Dries quietly r_3: Dries safely r_4:Less energy consumption r_5: Less material usage r_6: Low cost r_7 : Light weight r_8: Easy to disassemble r_9: Comfortable to hold r_{10}: Durable	m_1: Amount of energy m_2: Air flow m_3: Volume m_4: Lifespan m_5: Heat capacity m_6: Weight m_7: Types of materials m_8: Air temperature m_9: Noise and vibration m_{10}: Toxicity of materials	f_1: Generate air flow f_2: Heat air flow f_3: Control air flow f_4: Guide air flow f_5: Maintain temp f_6: Convert electricity f_7: Distribute electricity f_8: Dissipate heat f_9: Support hand	c_1: AC motor c_2: Fan c_3: Heating element (steel coil) c_4: Housing c_5: Fan housing c_6: Insulation cover c_7: Power switch c_8: Heating switch

3.8 Summary

This chapter has proposed a systematic approach of building relational matrices for reducing environmental impacts. The key technique of the proposed procedure is to integrate the functional descriptions of a product in the framework of QFD for eco-design improvement. The integration is done based on the unified relational models represented in a matrix format; these are *RM*, *MC* and *FC* matrices. The proposed procedure has been demonstrated through home appliances (i.e., a coffee maker and hair dryer). These models provide a solid framework to support the generation of design concepts for eco-design. The analysis of the proposed models is shown in the next chapter. The work which has been introduced in this chapter associated with concept generation, and with concept selection in Chapter 4 is published in a scientific conference[1] and a refereed journal[2].

[1] International Conference on Mechanical Engineering and Mechatronics, Toronto, Canada, 2013.

[2] International Journal of Mechanical Engineering and Mechatronics, Avestia Publisher, February, 2014.

Chapter 4 : Matrix-based Approach for Eco-Design Generation and Selection

In this chapter, our focus is to analyze the constructed relational models in Chapter 3. In our prior work, the relationship among the design elements is identified. The analysis of the constructed models leads to the generation and evaluation of new design concepts. In concept generation, the mapping between requirements and functions is determined via matrix multiplications. Then a morphological chart is established to generate possible design concepts. The generated concepts are evaluated using a Pugh chart via the delegated engineering metrics. A coffee maker and hair dryer have been used as case examples to demonstrate the proposed method for supporting eco-design.

4.1 Generation of Design Concepts

This methodical step has two parts. The first part is to determine the relational strength between requirements (*R*) and functions (*F*) for highlighting the functions for eco-design. The second part is to apply the morphological chart with highlighted functions to generate design concepts.

4.1.1 Determining *RF* Matrix

As the literature background, the QFD tradition tends to focus on the customer aspects in view of requirements and emphasizes how these requirements can be deployed in product development. In contrast, the notion of functions can usually be found in the works of engineering design theory and methodology (Stone and Wood, 2000). On one side, QFD I and II deploy the process as requirements → metrics → components. On another side, the functional analysis (FA) also indicates the mapping of functions → components. Then, "components" become the common point for connecting requirements and functions. The advantage of mapping environmental requirements and design functions is that, engineers can analyze the energy and materials flow from top to down levels through the sub-functions. This analysis gives indication to design engineers that which functions may generate impacts on the environment. Figure 4.1 shows an illustration scheme of mapping requirements and functions (*RF*) based on a coffee maker example.

Let $RF = [rf_{ij}]$ be the matrix that captures the mapping between requirements and functions. Particularly, each matrix entry rf_{ij} indicates the relational strength between the ith requirement and the jth function, and the ranges of the subscripts are $1 \le i \le k$ and $1 \le j \le q$.

In the previous chapter, the practices of QFD and FA allow us to obtain three relational matrices: *RM*, *MC* and *FC*. Accordingly, these relational matrices can be used to determine *RF* matrix using the matrix multiplication, as formulated below in Equation (4.1).

$$RF = RM \times MC \times FC^T \tag{4.1}$$

The superscript T is referred to the transpose of the matrix. For example, by considering the matrices *RM*, *MC* and *FC* of the hair dryer example in Chapter 3, the resulting *RF* matrix can be determined as provided below.

$$RF = \begin{bmatrix} 1919 & 1591 & 463 & 582 \\ 1110 & 279 & 438 & 459 \\ 418 & 465 & 133 & 141 \\ 2079 & 1869 & 507 & 612 \end{bmatrix}$$

In literature, matrix multiplication has been applied to analyze the change propagation effect (Hamraz et al., 2013). The idea applied here is similar. Essentially, the evaluation of *RF* is based on tracking the possible paths from r_i and f_j via $R \rightarrow M \rightarrow C \rightarrow F$. To illustrate, Figure 4.2 shows the overall graphical mapping of the hair dryer example. Suppose that we want to evaluate the relational strength between r_1 and f_4. Then, two paths are found between them:

1. Path 1: $r_1 \rightarrow 9\ m_1 \rightarrow 3\ c_2 \rightarrow 3\ f_4$.

2. Path 2: $r_1 \rightarrow 9\ m_2 \rightarrow 9\ c_2 \rightarrow 3\ f_4$.

The superscript besides the arrow indicates the relational strength (e.g., $m_1 \rightarrow 3,\ c_2$ implies $mc_{12} = 3$). In matrix multiplication, the relational strengths on the same path are first multiplied (e.g., 9×3×3 = 81 for Path 1). Then, the products of all paths between r_1 and f_4 are added (i.e., 81+243 = 324) to determine the relational strength.

To make the relational strength applicable for practitioners, a normalization procedure is applied for the *RF* matrix. It is required to be applied to simplify the analysis of the matrix. First, the *RF* matrix is divided by the largest value of this matrix. Then, Table 4.1 is used to map the normalized value to the "1, 3, 9" scheme. For example, the resulting *RF* matrix of the hair dryer example after normalization (denoted as RF_n) is given below in Equation (4.2).

$$[RF_n] = \begin{bmatrix} 9 & 9 & 3 & 3 \\ 9 & 3 & 3 & 3 \\ 3 & 3 & 1 & 1 \\ 9 & 9 & 3 & 3 \end{bmatrix} \tag{4.2}$$

Table 4.1. Scheme for mapping normalized values to QFD ratings of the hair dryer

Normalized value	QFD rating (*RF* matrix)
Less than 0.01	0
Between 0.01 and 0.07	1
Between 0.07 and 0.35	3
More than 0.35	9

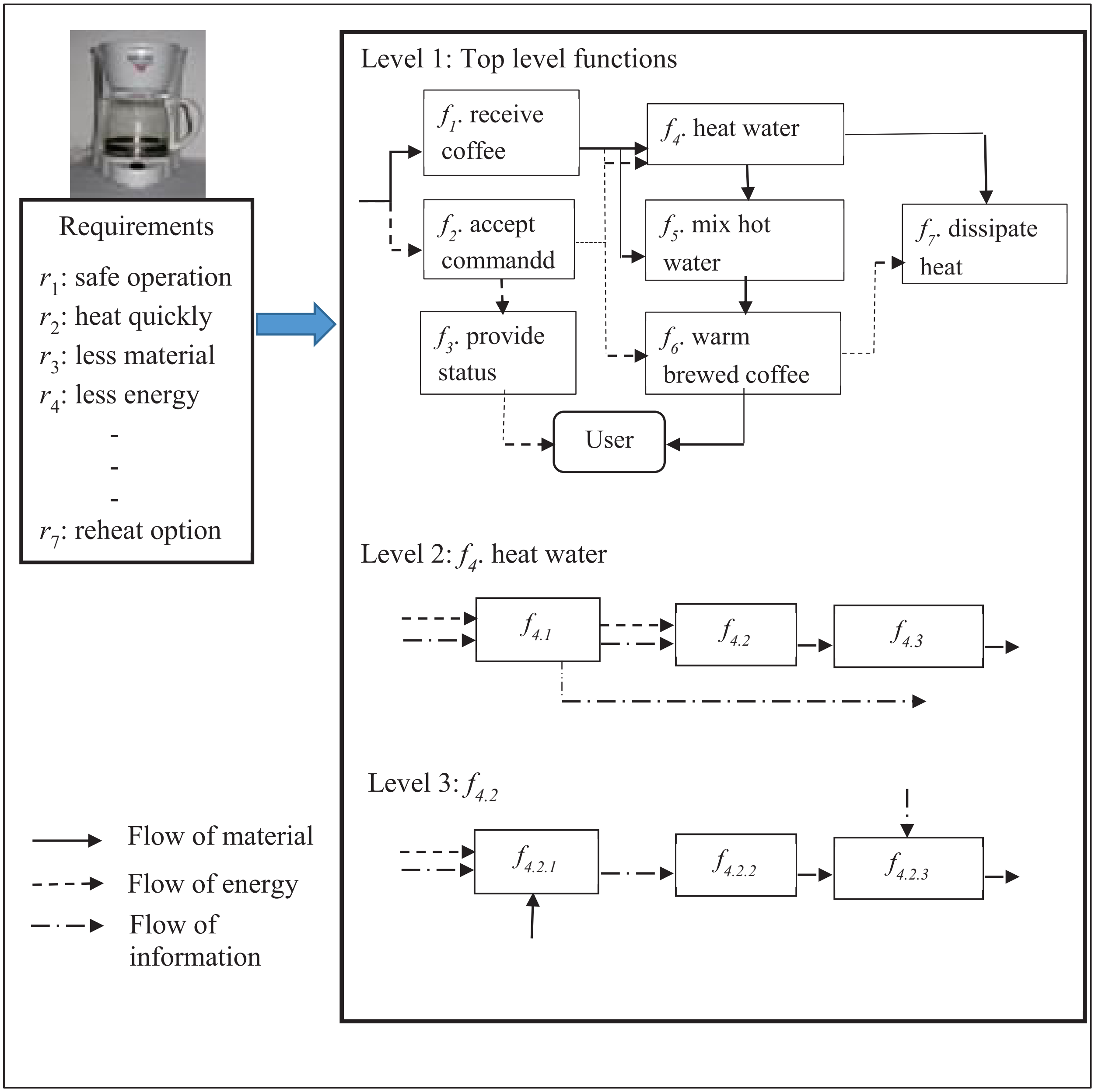


Figure 4.1. Schematic of mapping requirements and functions (RF)

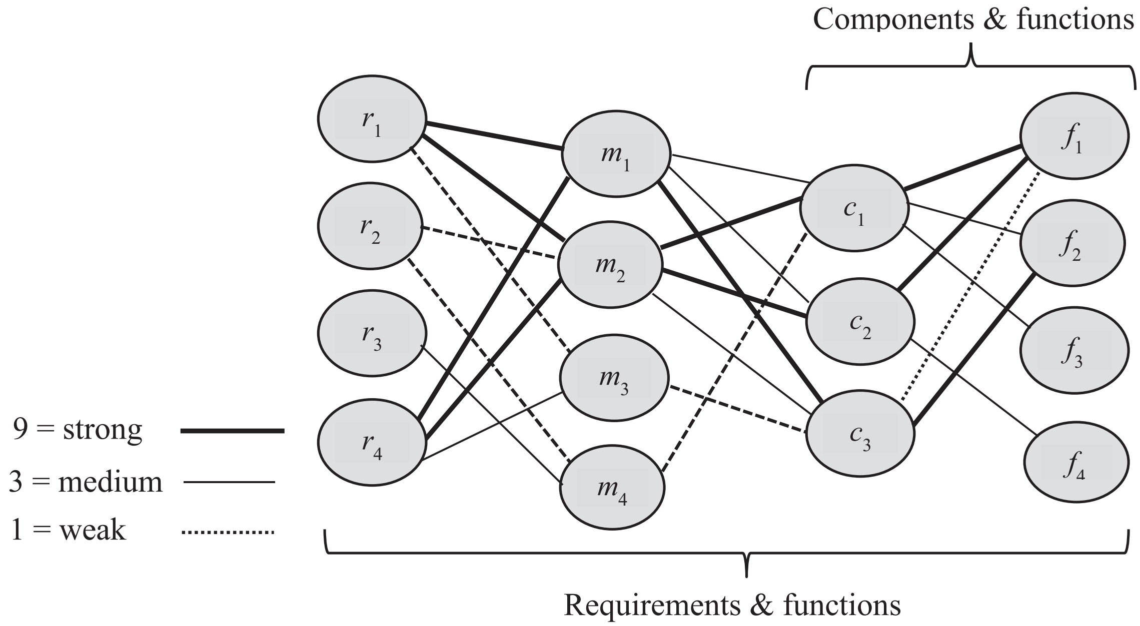


Figure 4.2. Mapping from requirements to components

4.1.2 Morphological Chart

After determining the *RF* matrix, the morphological chart is applied to generate design concepts. First of all, the requirements of the eco-design concern are highlighted. Via the *RF* matrix, the relevant functions can be identified. In the hair dryer example, suppose that "less energy consumption" (r_4) is the main concern. By checking RF_n matrix (Equation 4.2), this requirement is strongly related to f_1 (generate air flow) and f_2 (heat air flow). Then, engineers should devote more efforts on developing possible solutions for these two functions, while other functions (e.g., f_3 and f_4) would have less priority.

By using the morphological chart, it is expected that some functions can be potentially satisfied by multiple solutions. To generate a design concept, we need one solution for each function. In this case, the number of the possible design concepts can increase rapidly. Then, engineers should use their judgments to eliminate the least favorable concepts in view of their feasibility. Readers may refer to Lo et al., (2010) for more details of the morphological chart.

4.2 Concept Evaluation and Selection

In the case that multiple design concepts are generated, it is desired to shortlist some of them for further development. This engages the final stage "concept evaluation and selection". Notably, this topic has been widely studied, and this study is not intended to advance on this issue. Instead, we try to utilize the information of relational matrices in Chapter 3 and apply a quality tool for this stage of work. In this consideration, the Pugh selection method is used due to its simplicity and the well-recognized matrix format (Brue and Launsby, 2003).

Generally, the Pugh selection method evaluates design concepts by comparing them with the datum design. In our case, the datum design is the original design, from which we want to evaluate how well the design concepts can be improved from the eco-design aspects. The evaluations are based on metrics (*M*) that are discussed in the previous chapter. Three symbols are used to indicate whether a new design concept has a better (symbolized as '+'), poorer (symbolized as '-') or same (symbolized as 's') metric performance as compared to the original design. A sample Pugh chart is illustrated in Figure 4.3.

In this study, the symbolic evaluations in the Pugh method are only treated as the referential base for engineers to select the design concepts. So it is advised not to just count the number of symbols to conclude the goodness of the design concepts. Since this work is mainly concerned with concept generation, the detailed and quantitative evaluation methods are not covered. Notably, in spite of its simplicity, the Pugh selectin method remains a popular and well-recognized tool in six sigma management. In the next sub-sections, practical case examples are used to demonstrate the methodology approach to support eco-design at the conceptual design stage.

Criteria	Original design	Concept (x)	Concept (y)	Concept (z)
m_1		+	-	+
m_2	s	-	+	+
m_3	s	+	s	s
Total score		$\sum$ of + 2	$\sum$ of + 1	$\sum$ of + 2
		$\sum$ of - 1	$\sum$ of - 1	$\sum$ of - 0

Figure 4.3. Pugh chart of concept selection

4.3 Example: Coffee Maker

4.3.1 Translation of Environmental Requirements to Functions

Suppose that the incoming environmental requirement is the reduction of energy consumption of the coffee maker. From the *RM* matrix, it is related to r_{10}. The r_{10} is highlighted to track the related metrics, which are m_1, m_2, m_7, m_8 and m_{10}. Here, m_8 is removed from further mapping since it has a relatively weaker relationship to r_{10}. In addition, the *RF* matrix is identified based on *RM*, *MC* and *FC* matrices via Equation (4.1). The results of *RF* matrix show large values. After that, normalization is employed and the RF_n matrix result is determined. By checking the relational strengths in the RF_n matrix, it is shown that the functions f_5, f_6, f_7, f_8 and f_9 have strong relations with the eco-design requirements r_{10}. Then, based on the identified functions engineers can systematically generate various design concepts using morphological chart.

$$[RM] = \begin{bmatrix} 0 & 0 & 0 & 3 & 3 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 9 & 0 & 3 & 0 & 0 \\ 9 & 9 & 0 & 1 & 0 & 0 & 9 & 3 & 0 & 9 \\ 0 & 0 & 9 & 3 & 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 0 & 0 & 9 & 0 & 1 \\ 0 & 0 & 0 & 9 & 0 & 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 3 & 0 \\ 9 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 3 & 9 & 9 & 3 & 0 & 0 & 0 \\ \mathbf{9} & \mathbf{9} & 0 & 0 & 0 & 0 & \mathbf{9} & 3 & 0 & \mathbf{9} \\ 0 & 0 & 0 & 0 & 0 & 9 & 9 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 \end{bmatrix}$$

$$RF = \begin{bmatrix} 008 & 0114 & 0129 & 0099 & 0090 & 0075 & 0120 & 061 & 0169 \\ 063 & 0270 & 0621 & 0567 & 0189 & 0207 & 387 & 279 & 1284 \\ 72 & 1218 & 1431 & 1323 & 4977 & 3564 & 5607 & 2118 & 3258 \\ 198 & 1089 & 1890 & 1350 & 0135 & 0126 & 468 & 0414 & 1293 \\ 162 & 892 & 1575 & 1251 & 0486 & 0408 & 0843 & 552 & 1740 \\ 012 & 117 & 0279 & 261 & 243 & 0198 & 333 & 0174 & 0486 \\ 057 & 369 & 540 & 0360 & 054 & 0054 & 0135 & 108 & 291 \\ 000 & 289 & 0090 & 0090 & 1647 & 1191 & 1761 & 579 & 543 \\ 48 & 342 & 630 & 558 & 270 & 252 & 468 & 300 & 1287 \\ 72 & 1215 & 1431 & 1323 & 4968 & 3555 & 5598 & 2115 & 3255 \\ 99 & 540 & 1458 & 1350 & 675 & 558 & 1143 & 720 & 2661 \\ 7 & 42 & 123 & 117 & 72 & 60 & 114 & 68 & 246 \\ 0 & 252 & 81 & 81 & 1458 & 999 & 1512 & 513 & 432 \end{bmatrix}$$

Table 4.2. Scheme for mapping normalized values to QFD ratings of the coffee maker

Normalized value	QFD rating (*RF* matrix)
Less than 0.01	0
Between 0.01 and 0.09	1
Between 0.09 and 0.3	3
More than 0.3	9

$$RF_n = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 3 & 3 & 1 & 1 & 1 & 1 & 3 \\ 1 & 3 & 3 & 3 & 9 & 9 & 9 & 9 & 9 \\ 1 & 3 & 9 & 3 & 1 & 1 & 1 & 1 & 3 \\ 1 & 3 & 3 & 3 & 1 & 1 & 3 & 3 & 9 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 3 & 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 3 & 3 & 9 & 3 & 3 \\ 0 & 1 & 3 & 1 & 1 & 1 & 1 & 1 & 3 \\ \mathbf{1} & \mathbf{3} & \mathbf{3} & \mathbf{3} & \mathbf{9} & \mathbf{9} & \mathbf{9} & \mathbf{9} & \mathbf{9} \\ 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 9 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 3 & 3 & 3 & 3 & 1 \end{bmatrix}$$

4.3.2 Generation of Design Concepts

The below functions are highlighted for eco-design improvements based on the results of RF_n.

1. f_5: Distribute electricity

2. f_6: Heat water
3. f_7: Warm brewed coffee
4. f_8: Dissipate heat
5. f_9: Distribute weight

The constructed morphological chart for this application is shown in Figure 4.4. The first column of the morphological chart lists the functions of the coffee maker. Then, engineers are asked to propose possible solutions for each function. For example, to warm brewed coffee (i.e., f_7), the "hot plate" or the "insulated cup", which are listed as possible conceptual solutions can be used to achieve this function. Then, engineers can combine various conceptual solutions to come up with various design concepts.

By focusing on the relevant functions, which are identified in the previous step, engineers need to investigate the opportunities for reducing energy consumption. When considering f_6 (i.e., Heat water), it is noted that there should be some better ways to "insulate the energy flow," which becomes a new function for new design opportunities. This new function is also included in the morphological chart. The three design concepts which have been proposed in this work are discussed as follows.

- Concept '*x*': This concept is quite similar to the original design and intended to maintain the used energy by insulating the temperature. It includes large heating plate and hot plate. Thus, the energy consumption is expected to be minimized after applying the insulations. Also, the focus is to insulate the temperature by using O-ring for fixing the components. In view of the used materials, it is frequently used consumed papers. Once consumed papers are used, the anticipated impact is high. The reheat option is considered when the hot plate is included. The hot plate is essential for this concept and the suggested material for the plate is aluminum.

- Concept '*y*': This concept is intended to reduce the energy consumption by using an insulated jug instead of the carafe so that the hot plate for warming brew coffee (f_7) is illuminated. Since there is no reheat option, the expected energy is low. Besides, there is no paper filter, it was replaced by permanent plastic filter.
- Concept '*z*': This concept is intended to reduce material usage by replacing paper filters with a permanent steel filter. In this case the original housing structure requires to be modified to fix the permanent filter. The three design concepts of the coffee maker are shown in Figure 4.5.

Functions	Possible conceptual solutions		
f_5: Distribute electricity	Cord		
f_6: Heat water	Submersible element	Large heating plate	
f_7: Warm brewed coffee	Hot plate	Insulated jug	
f_8: Dissipate heat	Temp insulation	Seal covers	
f_9: Distribute weight	Minimize heavy Material	Disassemble parts (carafe)	
Insulate energy flow	Rubber O-ring	Screws	Grommet sealing

Figure 4.4. Morphological chart for concept generation of the coffee maker

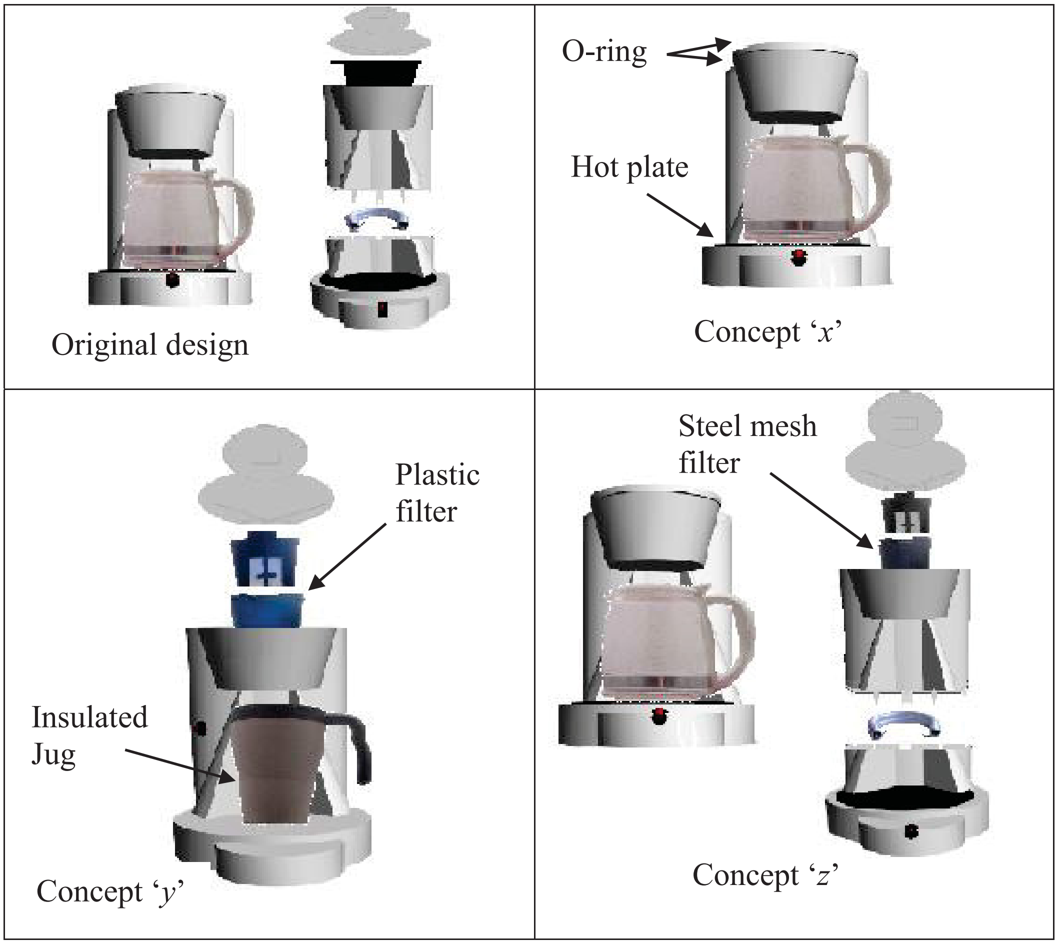


Figure 4.5. Design concepts of the coffee maker

4.3.3 Evaluation and Selection of Design Concepts

By checking *RM* matrix result, it has been identified that metrics m_1, m_2, m_7 and m_{10} are relevant to this eco-design. Thus, the proposed design concepts are evaluated with these metrics using Pugh chart. The evaluation results are provided in Figure 4.6. The evaluation starts by examining the advantages and disadvantages of the proposed concepts. In terms of energy consumption, concepts ‘*x*’ and ‘*y*’ perform better due to the proposed new components (i.e., insulations and insulated jug) for maintaining the energy. While the insulated cup can give advantage of low energy consumption in concept ‘*y*’, it gives negative impact in the same concept for the thermal distribution (m_2) and for the absent of the reheat option (m_{10}). Besides, it is clear that permanent filters can provide the advantage in view of material types (m_7) for concepts '*y*' and '*z*'.

After the discussion and the overall assessment, engineers can consider the Concept '*z*' is the promising design for reducing environmental impacts. They can also select and replace the component(s) that they think it makes better contribution for reducing environmental impacts. For example, using insulations to maintain the energy might add positive value.

	Concept '*x*'	Concept '*y*'	Concept '*z*'
m_1: Amount of energy	Better due to the use of insulations	Better due to an insulated jug	Similar to the original
	Evaluation: +	**Evaluation: +**	**Evaluation: s**
m_2: Thermal distribution	Better due to the use of aluminum and steel plates	Worse due to the plastic jug	Better due to the use of aluminum and steel plates
	Evaluation: +	**Evaluation: -**	**Evaluation: +**
m_7: Types of material	Worse due to the use of consumed papers	Better due to the use of insulated jug and permanent plastic filter	Better due to the use of permanent filter
	Evaluation: -	**Evaluation: +**	**Evaluation: +**
m_{10}: Reheat option	Similar to the original	Worse due to the plastic jug	Similar to the original
	Evaluation: s	**Evaluation: -**	**Evaluation: s**
	Number of '+' = 2 Number of '-' = 1 Number of 's' = 1	Number of '+' = 2 Number of '-' = 2 Number of 's' = 0	Number of '+' = 2 Number of '-' = 0 Number of 's' = 2

Figure 4.6. Pugh selection chart of the coffee maker example

4.4 Example: Hair Dryer

4.4.1 Translation of Environmental Requirements to Functions

In this study, the reduction of the energy consumption (r_4) and the minimum materials usage (r_5) are set as the goals for eco-design improvement. The corresponding rows in the *RM* matrix are highlighted for emphasis. It is found that these two requirements have strong relations to m_1, m_2, m_3, m_6, and m_7 and relatively weak or no relations to m_4, m_5, m_8, m_9 *and* m_{10}. Moreover, based on *RM*, *MC* and *FC* matrices, the *RF* matrix is determined via Equation (4.1). After the normalization process discussed in Section 4.1, the RF_n matrix result is also determined. In the matrix RF_n, it is shown that the functions f_1, f_2, f_5 and f_6 have strong relations with the eco-design requirements r_4 and r_5. Then, engineers can initially focus on these four functions for eco-design improvement.

The eco-design requirements are mapped to design functions systematically, allowing the application of the morphological chart for concept generation and subsequently the Pugh chart for concept selection.

$$[RM] = \begin{bmatrix} 9 & 9 & 0 & 0 & 1 & 0 & 1 & 3 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 9 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 & 1 & 3 & 1 & 3 \\ \mathbf{9} & \mathbf{9} & \mathbf{0} & \mathbf{0} & \mathbf{3} & \mathbf{0} & \mathbf{3} & \mathbf{3} & \mathbf{0} & \mathbf{0} \\ \mathbf{3} & \mathbf{0} & \mathbf{9} & \mathbf{0} & \mathbf{0} & \mathbf{9} & \mathbf{3} & \mathbf{0} & \mathbf{0} & \mathbf{3} \\ 0 & 0 & 1 & 0 & 0 & 1 & 3 & 0 & 3 & 3 \\ 0 & 0 & 9 & 0 & 0 & 9 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 1 & 0 & 1 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 3 & 0 & 9 & 0 & 0 & 0 \end{bmatrix}$$

$$RF = \begin{bmatrix} 1919 & 1591 & 463 & 582 & 831 & 853 & 528 & 1331 & 232 \\ 1110 & 279 & 438 & 459 & 464 & 779 & 5 & 19 & 1 \\ 418 & 465 & 133 & 141 & 234 & 315 & 120 & 355 & 37 \\ \mathbf{2079} & \mathbf{1869} & \mathbf{507} & \mathbf{612} & \mathbf{909} & \mathbf{963} & \mathbf{594} & \mathbf{1575} & \mathbf{264} \\ \mathbf{1455} & \mathbf{945} & \mathbf{636} & \mathbf{576} & \mathbf{741} & \mathbf{1173} & \mathbf{327} & \mathbf{543} & \mathbf{147} \\ 533 & 301 & 247 & 240 & 295 & 471 & 64 & 135 & 20 \\ 1128 & 531 & 507 & 477 & 558 & 909 & 162 & 219 & 75 \\ 175 & 163 & 88 & 90 & 122 & 151 & 41 & 110 & 13 \\ 144 & 61 & 69 & 63 & 76 & 123 & 22 & 17 & 10 \\ 321 & 633 & 111 & 108 & 219 & 231 & 138 & 561 & 54 \end{bmatrix}$$

$$RF_n = \begin{bmatrix} 9 & 9 & 3 & 3 & 9 & 9 & 3 & 9 & 3 \\ 9 & 3 & 3 & 3 & 3 & 9 & 0 & 0 & 0 \\ 3 & 3 & 1 & 1 & 3 & 3 & 1 & 3 & 0 \\ \mathbf{9} & \mathbf{9} & \mathbf{3} & \mathbf{3} & \mathbf{9} & \mathbf{9} & \mathbf{3} & \mathbf{9} & \mathbf{3} \\ \mathbf{9} & \mathbf{9} & \mathbf{9} & \mathbf{3} & \mathbf{9} & \mathbf{9} & \mathbf{3} & \mathbf{3} & \mathbf{1} \\ 3 & 3 & 3 & 3 & 3 & 3 & 1 & 1 & 0 \\ 9 & 3 & 3 & 3 & 3 & 9 & 1 & 3 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 3 & 9 & 1 & 1 & 3 & 3 & 1 & 3 & 0 \end{bmatrix}$$

4.4.2 Generation of Design Concepts

Based on the results of RF_n from the previous sub-section, the functions that are highlighted for eco-design improvements are listed below.

1. f_1: Generate air flow
2. f_2: Heat air flow
3. f_5: Maintain temperature
4. f_6: Convert electricity

Then, the possible solutions are studied for satisfying these four functions and construct the morphological chart, which is shown in Figure 4.7. These solution options can help engineers explore different components for satisfying r_4 and r_5. For example, to heat air flow (i.e., f_2), we may suggest the material of the "heating element" a coil made of steel or nickel chromium, or the heating source might be from nickel ceramic. Accordingly, three design concepts are generated, and they are described as follows.

- Concept '*x*': This concept is the simplest and quite similar to the original design. In this concept, it is planned to reduce the electricity consumption by replacing the AC motor to the DC motor. The potential advantage is to minimize the electricity consumption with the increase of rotational speed (RPM) and the air flow. Moreover, the DC motor can drop the voltage by connecting it with a converter and adding the batteries to charge the hair dryer whenever it is needed. Thus, based on the above description, applying this concept may lead to energy consumption minimization. Figure 4.8 illustrates the proposed concept '*x*'.
- Concept '*y*': This concept is intended to replace the heating source material to reduce the energy consumption. Particularly, an infrared heating element, nickel ceramic, is suggested to replace steel coil. The potential advantages of this element include efficient energy use (due to the reduction of the emitted radiations) and longer lifespan. Moreover, a brass insulation cover is suggested to save the heating time. A removable filter is proposed to absorb the dust that may enter the hair dryer during both the use and the non-use time. Figure 4.9 illustrates the proposed concept '*y*'.
- Concept '*z*': This concept is intended to minimize the material usage of the hair dryer. The primary materials of this design concept are polystyrene, mica, and steel. The proposed concept uses the DC motor, an auto-off switch and a cordless system. Figure 4.10 illustrates the proposed concept '*z*'.

The characteristics of these design concepts are summarized in Table 4.3 for highlighting their differences. After concept generation, the next sub-section will discuss the assessment of these concepts using the Pugh selection method.

Functions	Possible conceptual solutions		
f_1: Generate air flow	Fan (Polypropylene)	Fan (Polycarbonate)	Fan (Polystyrene)
f_2: Heat air flow	Heating element (Steel coil)	Infrared heating element (Nickel ceramic coil)	Heating element (Nickel chromium coil)
f_5: Maintain temp	Insulation cover (Mica)	Insulation cover (Brass)	
f_6: Convert electricity	AC motor	DC motor	

Figure 4.7. Morphological chart for concept generation of the hair dryer

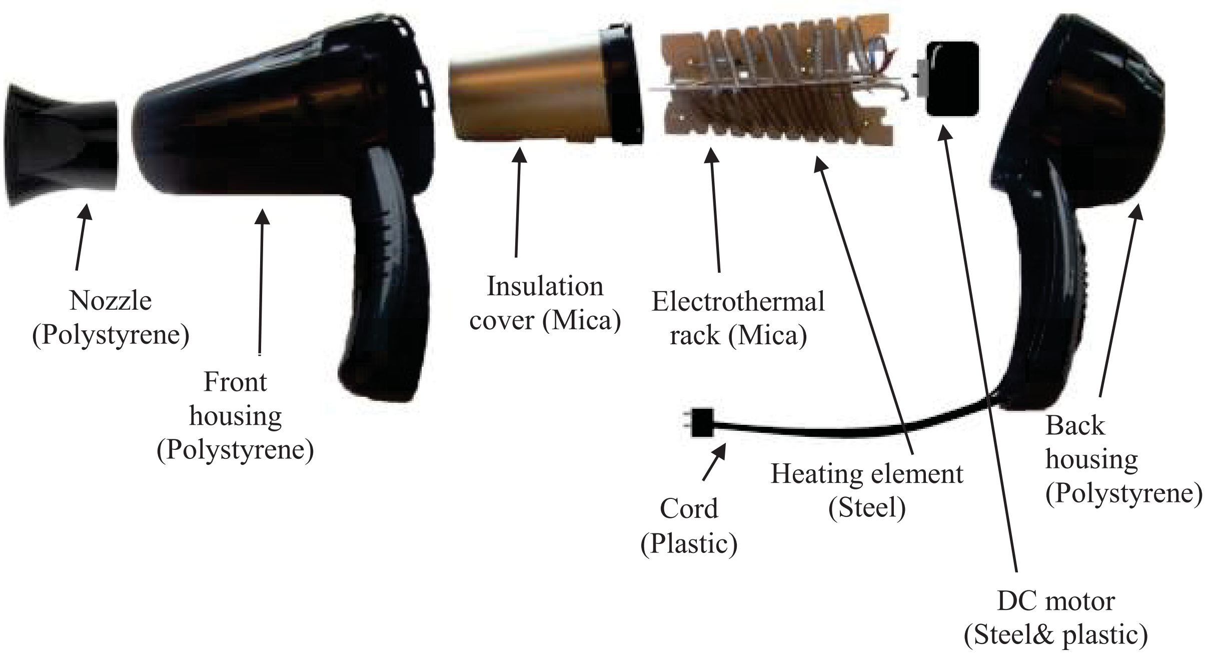


Figure 4.8. Design concept '*x*' of the hair dryer

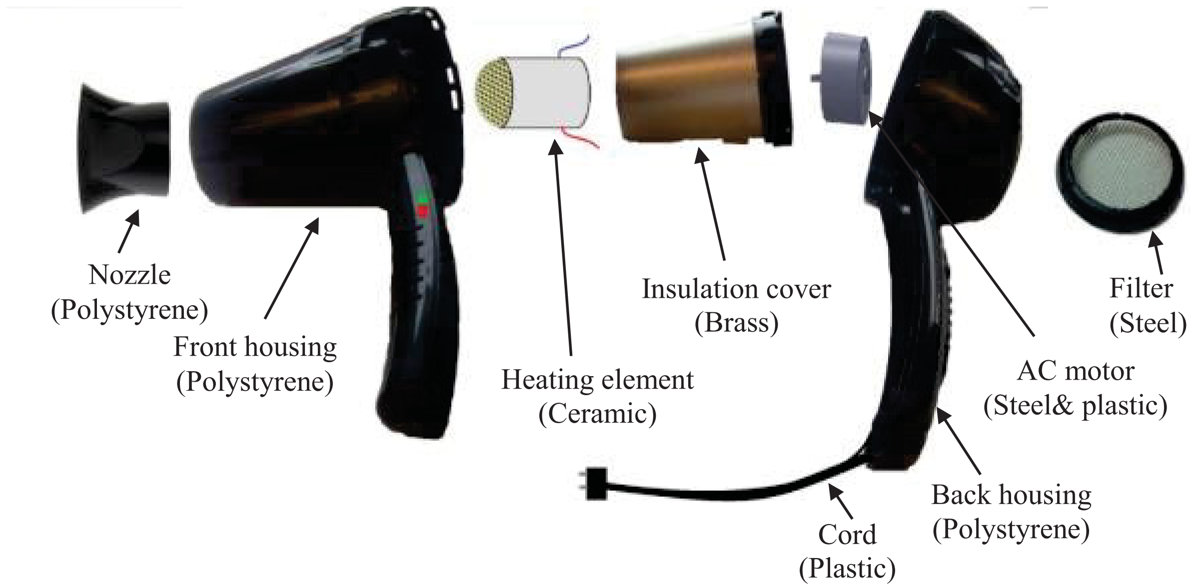


Figure 4.9. Design concept '*y*' of the hair dryer

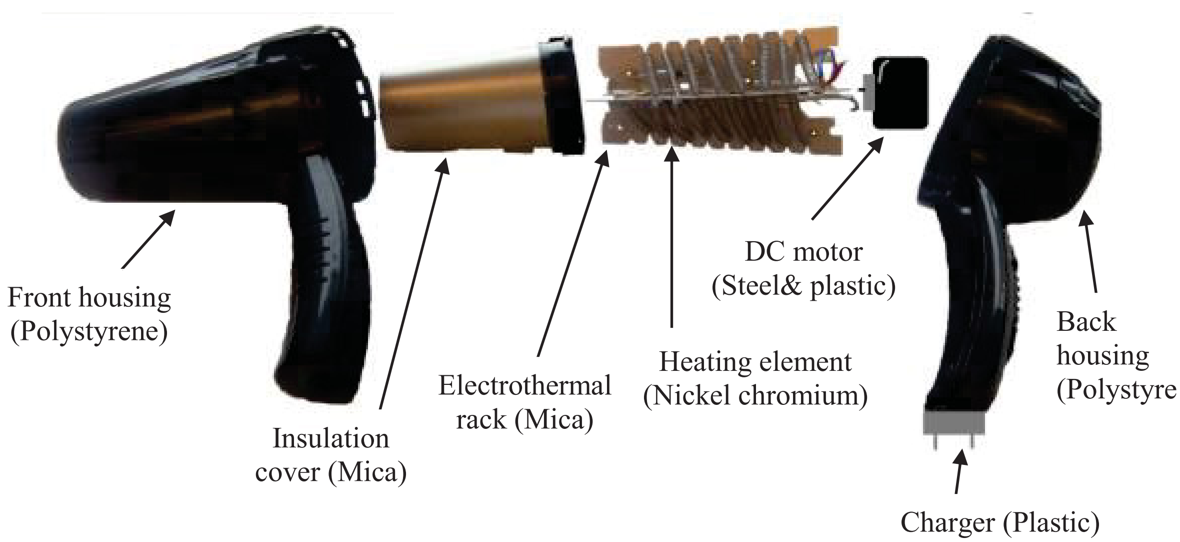


Figure 4.10. Design concept '*z*' of the hair dryer

Table 4.3. Characteristics of three design concepts

	Key design idea	Trade-off	Impact consequences
Concept '*x*'	Use DC motor to reduce electricity consumption	DC motor requires maintenance because it contains carbons	Low because has less energy consumption and light weight that may contribute to reduce environmental impact
Concept '*y*'	Use infrared heating element (Ceramic coil) that utilizes the energy efficiently	More material usage, energy requires an orientation	Medium because design includes more material and contains AC motor
Concept '*z*'	Reduce material usages	Less materials difficult to guide energy to be isolated	Medium because includes DC motor and has no nozzle

4.4.3 Evaluation and Selection of Design Concepts

By referencing the *RM* matrix in Equation (4.1), the metrics m_1, m_2, m_3, m_6 and m_7 are mainly used to evaluate two eco-design requirements, r_4 and r_5, which have been specified earlier. Using the Pugh selection chart, the evaluation results are provided in Figure 4.11. Instead of checking the "overall scores", it is worthwhile at the conceptual stage to examine the pros and cons of each design concept.

First of all, three design concepts are expected to improve m_1 (amount of energy) and m_2 (air flow) due to the use of DC motors, new heating elements and the nozzle. Yet, as the nozzle can negatively impact m_3 (size), concept '*z*' performs better in this metric. While the DC motor can give the advantage of lighter weight (m_6) for concept '*x*' and '*z*', new heating elements can provide the advantage in view of material types (m_7) for concepts '*y*' and '*z*'.

Based on the above analysis, engineers do not have to stick with one design concept or another. Instead, they can further analyse and revise the design concepts. For example, as the DC motor seems to be a promising idea (more energy efficient and lighter weight), how much energy it can potentially save as compared to the original design? Does the DC motor have some drawbacks? In addition, as the use of alternate heating elements (versus steel coils) seems to have a good potential, engineers can start to think about the component suppliers and associated costs for checking the economic feasibility.

	Concept ‘*x*’	Concept ‘*y*’	Concept ‘*z*’
m_1: Amount of energy	Better due to DC motor	Better due to ceramic heating element	Better due to DC motor
	Evaluation: +	**Evaluation: +**	**Evaluation: +**
m_2: Air flow	Better due to increased RPM from DC motor	Better due to the nozzle	Better due to increased RPM from DC motor
	Evaluation: +	**Evaluation: +**	**Evaluation: +**
m_3: Size	Worse due to the added nozzle	Worse due to the added nozzle and filter	Similar to the original
	Evaluation: -	**Evaluation: -**	**Evaluation: s**
m_6: Weight	Better due to lighter DC motor	Worse due to added filter and ceramic component	Better due to lighter DC motor
	Evaluation: +	**Evaluation: -**	**Evaluation: +**
m_7: Types of materials	Similar to the original	Better due to the ceramic component	Better due to the Nickel chromium
	Evaluation: s	**Evaluation: +**	**Evaluation: +**
	Number of ‘+’ = 3 Number of ‘-’ = 1 Number of ‘s’ = 1	Number of ‘+’ = 3 Number of ‘-’ = 2 Number of ‘s’ = 0	Number of ‘+’ = 4 Number of ‘-’ = 0 Number of ‘s’ = 1

Figure 4.11. Pugh selection chart of the hair dryer example

4.5. Discussion of the Method

The proposed method of this thesis supports engineers for eco-design improvements in two aspects. Firstly, engineers can capture the design information in a relatively simple form, i.e., relational matrices. As a recall, the construction of relational matrices is based on some well-known quality tools, i.e., QFD and functional analysis, which often focus on the weightings for the overall customer satisfaction. In our view, the uniqueness of eco-design is that engineers tend to have a clear goal about what needs to be improved in eco-design (e.g., reduce energy use). Then, relational matrices represent some forms of "information template" that guides engineers what design information needs to be collected for eco-design improvements.

Secondly, the design information can be quite substantial even for a typical product. For example, in the hair dryer design, the relational matrices already capture 10 requirements, 10 metrics, 9 functions and 8 components (see Table 3.3). The proposed method of this study can help engineers identify the important functions for concept generation. In the same example, four functions are suggested (instead of considering 9 functions), as shown in Figure 4.7 for improving the hair dryer design. Setting up such priority can help allocate design efforts (e.g., identify and investigate the potentials of DC motors).

In practice, based on the engineers' experience, they may also be able to identify the significant functions for eco-design improvements. Yet, when the design of the products gets complex, such experience-based insights may not be reliable. The systematic mapping in the proposed procedure can help engineers sort out the details and identify the eco-design focus. In the next chapter, the methodical procedure for supporting eco-design improvement at the conceptual design stage will be presented in a manufacturing machine, which is related to forming process.

4.6 Summary

In this chapter, the analysis of the relational matrices models is proposed to support the conceptual design stage for reducing environmental impacts. The analysis procedure is accomplished by deriving the *RF* matrix based on matrix multiplication to translate eco-design requirements into design functions. Then, design concepts are generated based on design functions to select the promising design concept. The procedure is demonstrated using a coffee maker and hair dryer as examples. The above presented work is submitted to a refereed journal[3] for publication.

[3]International Journal of Concurrent Engineering: Research and Applications , 2015.

Chapter 5 : Eco-Design Improvement for the Diaphragm Forming Process

The purpose of this chapter is to demonstrate how the eco-design concept generation method (proposed in Chapters 3 and 4) can be applied to a manufacturing process. As it is planned to submit the work of this chapter to International Journal of Sustainable Engineering, the methodical contents of this chapter are simplified for the journal readership. Compared to the contents in Chapters 3 and 4, the methodical differences are listed as follows.

1. Only the requirements and metrics directly related to eco-design are listed, leading to a smaller requirement-metric matrix (i.e., smaller *RM*).
2. The binary matrix is used for the function-component matrix (i.e., *FC*) for simplicity.
3. The theme of concept selection is explicitly discussed; however, the evaluation of design concepts in this work is based on two metrics that are common in eco-design: energy use and processing time.

5.1 Introduction

Sustainable manufacturing (or and environmentally conscious manufacturing) has become an essential issue in a manufacturing society. In this study, towards sustainable manufacturing, eco-design is considered to reduce environmental impacts. Eco-design is a method used for environmental concerns, which pays attention to the life cycle assessment (LCA) of a product (Abele et al., 2005; Fiksel, 2009). Thus, eco-design is a strategy of sustainable manufacturing and can lead products and manufacturing systems to be more environmentally benign. Manufacturing sustainability has been introduced extensively in a review paper in sustainable manufacturing by (Haapala et al., 2013). Manufacturing process is usually considered in sustainability and is a wide issue comprises different manufacturing methods such as molding, additive manufacturing, and forming. In this chapter, our concern is about forming process.

In response to the research in sustainability, researchers have extended the practice of LCA to the forming processes of the sheet metal (Ingarao et al., 2011). Their concerns are to use materials and energy more efficiently. The investigated processes were based on experimental works and concluded that using different materials can lead to various material and energy savings. Gutowski et al., (2006) reported that the energy requirements for the manufacturing process are not the same, due to the different use of process rate. They have also suggested an approach to reduce the energy use by redesigning the manufacturing process.

Another research considered energy reduction (Haapala et al., 2012). The article developed a process modeling method to improve the environmental performance of metal casting. They claimed that the decrease of the electricity consumption can be obtained via preheating the material scrap, which is required for charging the furnace (Jacobus et al., 2001). Guiding energy and resources systematically by using methods in manufacturing process can improve the environmental performance (Duflou et al., 2012).

Several researchers have developed methodologies for the purpose of environmental impacts reduction, ranging from a generic method for calculating energy and mass losses using engineering guidelines and industrial experience (Overcash et al., 2009) and a framework for life cycle assessment (LCA) to analyze the inventory of manufacturing unit process (Gibovic and de Ciurana, 2008; Kellens et al., 2012). Kim et al., (2014) presented sustainability improvement in manufacturing process based on a decision-guidance framework. This work was purposely employed to overcome the deficiency of LCA framework. Our research is intended to develop a methodology to guide the forming process for new eco-design ideas.

Besides the development of the methodologies for sustainability in manufacturing process, new methods are also presented in the context of remanufacturing process for quality purpose. For example, Jiang et al., (2014) have developed a decision plan method for remanufacturing process selection. The QFD (i.e., quality function deployment) and fuzzy linear regression are integrated to identify the relationships between the remanufacturing performance and process quality. These refer to the need of new methods to efficiently reduce the environmental impacts. In the manufacturing process there is still a research gap of using quality tools for the purpose of environmental impacts reduction.

Further to the general review in sustainability in manufacturing process, it has been found that less research concerns improvement of environment in the applications of forming processes. Such research has been found in the application of cold roll forming process. For example, Paralikas et al., (2013) proposed the energy efficiency indicator method to estimate the energy consumption of the cold roll forming process. Furthermore, the knowledge management technique is used in cold roll-forming process as well. The research used knowledge management is studied (Oduoza and Harris, 2011). They claimed that supporting process development for decision making depends on information and knowledge. In forming process, in aluminum applications, concurrent engineering technique is used for process design integration. This approach is usually used for the metal processes and achieved by Bigot et al., (2003).

The main new contribution of this work is to develop a systematic procedure to guide the eco-design improvement of a forming process. Such procedure can be achieved by integrating quality function deployment (QFD) and functional analysis (FA) to enhance the concept generation of an existing forming process. As a first step, FA is integrated with the morphological chart to generate new design concepts. Yet, the developed approach is not shown in the research of the forming process.

The rest of this chapter is organized as follows. Section 5.2 provides an overview of the diaphragm forming process. Section 5.3 provides the eco-design improvement methodology. Section 5.4 applied the methodology to the diaphragm forming process (DFP). Section 5.5 concludes the chapter.

5.2 Overview of the Diaphragm Forming Process

Diaphragm forming is a method used for the production of aerospace parts. In the beginning the method is applied on a thermoplastic matrix composite. Then the method is extended to the application to the thermosetting matrix composite (Bersee et al., 2007). In this study the material, which is considered in the diaphragm forming process, is as general as a polymer matrix composite. The diaphragm forming is a process based on thermal energy. The energy of the process is a conversion from electrical to thermal energy. Thus, the major important physical component, which is basically considered in the process, is the heating source. The existing diaphragm forming machine from which the information is collected is still in the assembly stage. Notably, our methodology can be applied either for an existing product or a product which is not built yet but all its design information is documented. The detailed information about the general components of the diaphragm forming process (DFP) is explained in the next sub-sections.

The methods by which the forming process is accomplished can be classified into basic types such as compression molding, vacuum forming, and diaphragm forming (Long, 2007). In this study, DFP is chosen for the concept generation of the machine with environmental design consideration. Although the method has advantages compared to other forming processes such as the quality of the produced components, it has drawbacks though such as long cycle time (Tucker, 1997). The increase of the cycle time may cause the increase of the environmental impacts. This problem motivates the development of a framework that can lead to eco-design improvement of the original DFP.

5.2.1 Process Components

The process consists of two main parts. The first part is machine-based diaphragm forming and the second part is the autoclave which is used for curing the polymer composite. The main components of the process are identified as follows.

- Heating element: Used as a heating source to soften the material for the final shape.
- Diaphragm: During the forming process it translates the geometric deformation to the prepreg/ laminate and controls the forming stage. It is made of silicon rubber and is able to survive the high processing temperatures (e.g., from 350–400°C) without rupture.
- Vacuum pump 1: Used to draw the air which exists between the two diaphragms. The maximum vacuum pressure is about 100 KPa.
- Vacuum pump 2: Used to draw the air from the vacuum box. The maximum vacuum pressure is about 100 KPa.
- Vacuum box: The part where to place the mold and contains the air that needs to be drawn out.
- Mold: The part that uses to form the shape.
- Film: The material that is disposal and made from nylon or reusable silicon rubber. It is used to avoid sticky between the material and the mold.
- Autoclave: It is used to finish the complete polymerization. The autoclave temperature is above the polymer melting temperature and the autoclave pressure is up to 7 bar.

There are two important steps in the process of the diaphragm forming: (1) the forming process, and (2) the curing process. These two processes are identified and described in the next sub-sections.

5.2.2 Forming Process

The forming process of the two polymers, thermoplastic and thermoset composites, is quite similar. The difference is that the thermoset matrix is not melted before the forming stage but is heated to decrease the viscosity to allow the prepreg (polymer) to be formed. Essentially the forming process for the thermoset is an autoclave curing process. In the traditional forming process the polymer after the forming stage needs to be placed in an autoclave for the curing purpose. As a result, this step causes energy and time to be consumed. The main procedure of the DFP can be described as follows.

Firstly, in the DFP a composite prepreg / laminate is placed between two sheets (diaphragms) which are made from silicon rubber. The sheets are well clamped to avoid any defects on the formed shape. Then, the heater is turned up to warm up the material until the temperature distribution is guaranteed to be distributed evenly on the material. Next, the hydrostatic pressure is applied on the material during the process to create the deformation of the diaphragms (Smiley and Pipes, 1988). Subsequently, as far as the air between the two diaphragms is removed by a pump, then the force is transmitted to the diaphragm to form the polymer to the required shape. In addition, during the forming stage the diaphragms are stretched into the cavity of the mold under the atmosphere pressure. Finally, the part (i.e., the material) can be safely received after removing the two diaphragms. The part is then required to be placed in an autoclave for the purpose of curing (treatment). The curing of the part is described in the next sub-section. Figure 5.1 illustrates the main steps of the diaphragm forming process.

5.2.3 Curing Process

To achieve the curing step, the process involves placing the part in an autoclave. This requires placing the part under a vacuum and then pressurizing the autoclave during the heated cure cycle. The high pressure on the part helps to minimize resin (polymer) voids and to achieve the desired temperature. Autoclaves normally operate from 120 to 230 °C at 7 bars of pressure. Most common materials cured in an autoclave are advanced composites such as carbon fiber, epoxy resins etc. The curing cycle time can be estimated according to the used material and is generally 1.5 to 12 hours.

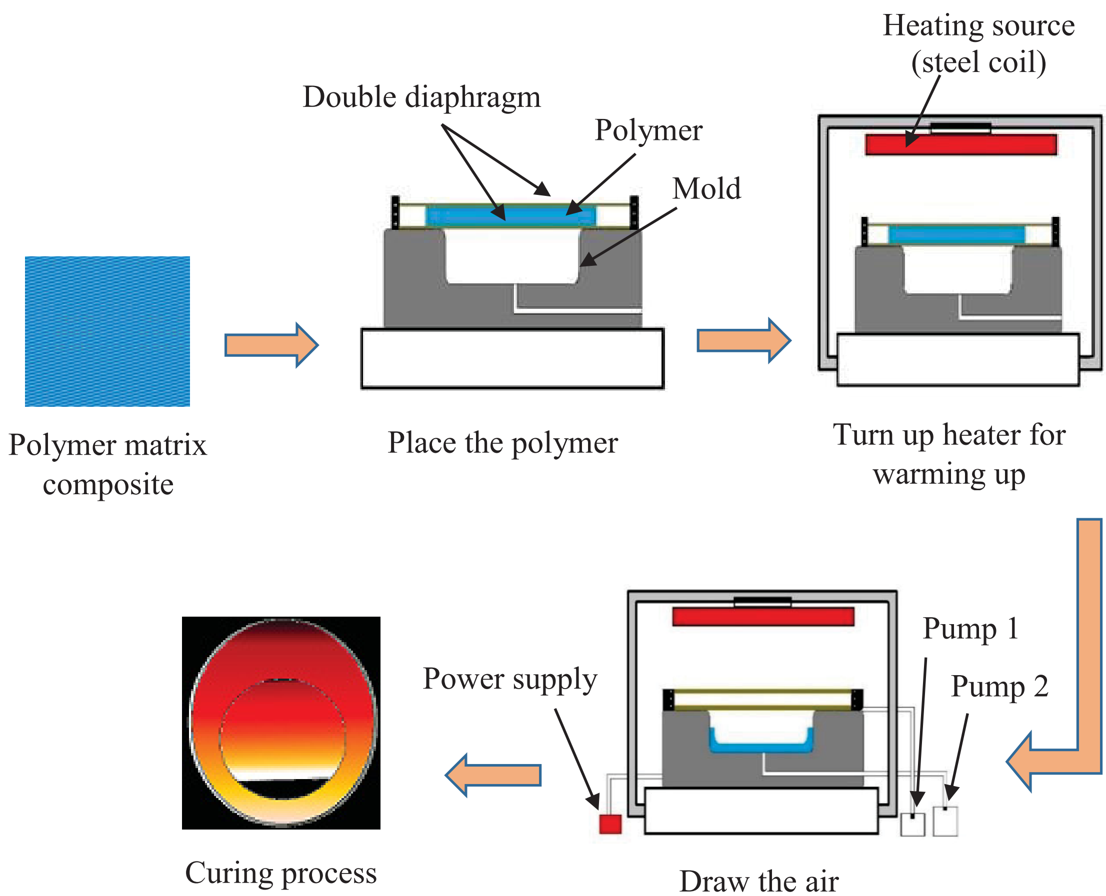


Figure 5.1. Schematic of diaphragm forming process

5.2.4 Remarks on the Diaphragm Forming Process

The diaphragm forming process (DFP) is observed as a relatively long process, wherein the consumption of the energy is high. Human input is essential and required for most of the stages of the process, and hence the time of the process has become long. Those observed problems may cause impacts on the environment. In this case, the principle idea for the new design process is to reduce the cycle time and to make the process more environmentally benign.

In the next section, an eco-design improvement method will be proposed and applied to the DFP. To better control the scope of the work, only the first step (i.e., the forming process) is included in this study. The design question here in practice is how to improve the existing forming process (as illustrated in Figure 5.1) for reducing environmental impacts. The next section is intended to address this question via a systematic method.

5.3 Methodology

The proposed method for eco-design improvement has four main steps, which are illustrated in Figure 5.2. The key idea of the proposed method is to map the eco-design requirements to the design functions, which are then used for generating new design concepts. These methodical steps will be further explained in this section.

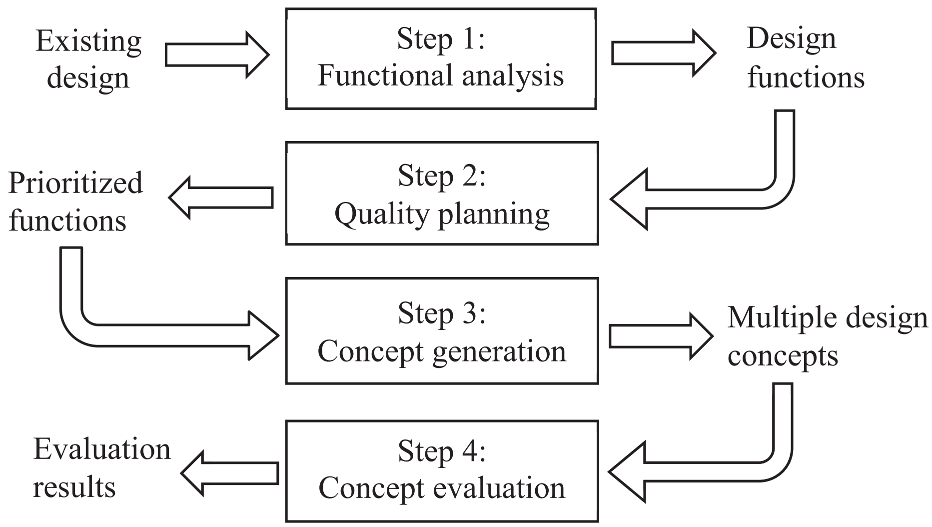


Figure 5.2. Workflow of the proposed method for eco-design improvement

5.3.1 Functional Analysis

Function is one foundational concept in design theory and methodology (Otto and Wood, 2001). The key idea of a function is to focus on the transformation between inputs and outputs. For example, the function of an electric motor is to convert the electrical energy to the mechanical torque. To highlight the transformation, it is common to describe a function using a format: verb + noun, such as “convert energy”. In such a functional description, the design engineer can “unlock” their mind from the object “motor” and start to brainstorm the possible solutions for achieving the function “convert energy”. This “form-follows-function” principle becomes the basic strategy for exploring new design concepts.

To analyze design functions systematically, three types of flows for functional inputs / outputs have been specified: material, energy and information (Otto and Wood, 2001). Figure 5.3 shows these three types of flows for the diaphragm forming process (DFP). The basic function of DFP is to convert a prepreg to a formed part, representing the material flow in bolded arrows in Figure 5.3.

It is expected that this DFP requires energy, thus the energy flow in narrow arrows. The information flow, represented in dashed arrows, signals the precedence and status of the manufacturing process.

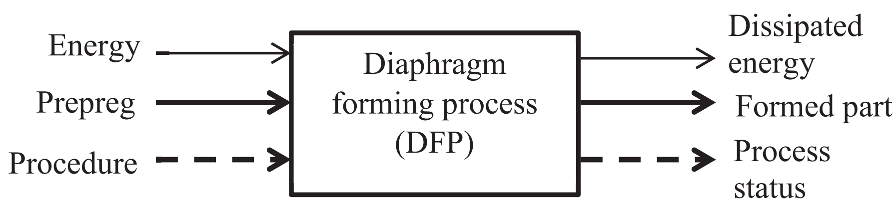


Figure 5.3. Three types of flows for the diaphragm forming process

The box in Figure 5.3 can be viewed as a "black box", in which engineers can design more specific details for the DFP. In literature, Otto and Wood, (2001) have suggested the identification of design functions via process descriptions. Let $F = \{f_1, f_2, \ldots\}$ be a set of design functions. By following the manufacturing steps described in Section 5.2, six functions (symbolized as f_1 to f_6) for the diaphragm are listed as follows.

1. f_1: import prepreg
2. f_2: tighten diaphragm
3. f_3: soften prepreg
4. f_4: shape prepreg
5. f_5: harden part
6. f_6: export part

Notably, these functions are described using the format "verb + noun". Also, these functions have the material / energy / information flows as functional inputs / outputs. As an example, Figure 5.4 illustrates the function, f_3 that takes the flow of heat energy to "soften the prepreg". The information flow indicates the signals of heat on / heat off. This functional description leaves some space for engineers to brainstorm the possible heating methods as an innovation process for eco-design improvement. By applying a similar analysis, the six functions of the DFP can be further developed and connected via their input / output flows, resulting in a functional diagram.

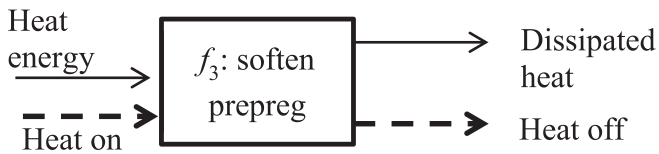


Figure 5.4. Illustration of functional description

To understand the existing design better, a function-component matrix is also constructed to show which existing components are used to achieve the functions. Let $FC = [fc_{ij}]$ be such a matrix, and $C = \{c_1, c_2, \ldots\}$ be the set of design components. If the component c_j is required to achieve the function f_i, then the matrix entry, fc_{ij}, is equal to 1 (otherwise, $fc_{ij} = 0$). The further information of the functional diagram and FC for the DFP will be provided in Section 5.4.

5.3.2 Quality Planning

Beyond customer satisfaction, the consideration of environmental issues has been another goal in the pursuit of quality for companies (McCarty et al., 2011). One common approach is to modify some existing quality tools for the eco-design purpose, and quality function deployment (QFD) has been commonly applied in this context. The initial effort can be found in the development of Green QFD (G-QFD) (Cristofari et al., 1996). Subsequently, some methodical extensions have been presented such as extending G-QFD to QFD II by integrating QFD and LCA to evaluate different design concepts (Rathod et al., 2011; Zhang, 1999).

In our view, the essence of QFD is the mapping between customer requirements and engineering metrics (Akao, 1990). While customer requirements highlight what customers want, the QFD mapping can associate which engineering metrics are important in view of customers. Then, these engineering metrics become a handle for engineers to improve existing products. In this context, let $R = \{r_1, r_2, \ldots\}$ and $M = \{m_1, m_2, \ldots\}$ be the sets of customer requirements and engineering metrics, respectively. Then, let $RM = [rm_{ij}]$ be the mapping matrix that corresponds to QFD. Usually, a 9-point scheme is applied to quantify rm_{ij} in QFD. For example, if r_i is strongly associated with m_j, rm_{ij} is equal to 9. For a medium or weak association, rm_{ij} is equal to 3 and 1, respectively. This common quantitative scheme of QFD is applied in this thesis.

In literature, RM is referred to the first mapping in QFD (or QFD I). Further mapping has also been proposed as QFD II, which maps from engineering metrics to design components (Akao, 1990). Recall that $C = \{c_1, c_2, \ldots\}$ be the set of design components. Let $MC = [mc_{ij}]$ be the mapping matrix between engineering metrics and design components. The same 9-point scheme is also applied to quantify the strength of association between the metric m_i and the component c_j as the common practice in QFD I and QFD II.

In sum, the intent of quality planning is to develop the mapping matrices RM and MC by following the practice of QFD. In the context of eco-design improvement, the environment serves as one type of customers, and its requirements can be expressed as a subset of R, which can be further mapped to M and C via RM and MC, respectively. The specifics of the DFP will be presented in Section 5.4.

5.3.3 Concept Generation

Concept generation here is carried out in two phases. The first phase is to utilize the matrix information (i.e., *RM*, *MC* and *FC* matrices) to prioritize the design functions identified in Section

5.3.1. In the second phase, the morphological chart is applied to the functions of high priority to generate design concepts for eco-design improvement.

The key technique of the first phase is matrix multiplication. As a logical chain, if the requirement r_i is strongly associated with the metric m_j (expressed in *RM*) and m_j strongly associated with c_k (expressed in *MC*), then r_i should be strongly associated with the component c_k. This logical chain can be formally determined via matrix multiplication (Hamraz et al., 2013). Given that "eco-requirements" are provided, the issue is to determine which functions are strongly associated with these eco-requirements for eco-design improvement. Let $RF = [rf_{ij}]$ be the mapping matrix between requirements and functions. Then, this matrix can be determined via the formulation below (where the superscript T means matrix transpose).

$$RF = RM \times MC \times FC^T \tag{5.1}$$

To explain the use of *RF*, suppose that one requirement, r_1, expresses "less energy use". Through the determination of *RF*, it is found that r_1 has the strongest association with f_3 "soften prepreg". With this information at hand, if the engineers want to improve the existing product in view of r_1 "less energy use", they should devote the efforts to think about alternate ways for achieving f_3 "soften prepreg". By prioritizing the functions, engineers can rank their efforts in what aspects of the product that should be explored for new solutions.

Given the prioritized functions, the morphological chart is applied for concept generation. The key of this chart is to ask the engineers the possible solutions for achieving each function. In this way, engineers can focus one function at a time, thus promoting the possibility of new ideas. To synthesize a design concept, engineers can pick one solution for each function based on their expertise and judgments. Notably, the morphological chart is well recognized as one concept generation method, and interested readers may refer to (Lo et al., 2010) for more details of the morphological chart.

5.3.4 Concept Evaluation

Multiple design concepts can be obtained from the morphological chart. At this point, several concept selection methods from literature can be applied such as multi-criteria decision making (Dieter and Schmidt, 2009). In this work, instead of determining a single design "winner", we focus on two eco-design aspects of the DFP: energy use and processing time. Then, new design concepts will be evaluated via the estimation of these two performance metrics. Further details can be provided in Section 5.4.

5.4 Methodical Application to the Diaphragm Forming Process

In this section, the methodology in Section 5.3 will be applied to the diaphragm forming process (DFP) and propose design concepts for eco-design improvement.

5.4.1 Functional Analysis and Quality Planning

In functional analysis, the DFP is first analyzed according to the manufacturing procedure described in Section 5.2, and these procedural steps are listed on the first column of Table 5.1. The actual function(s) of each step are then developed using graphical representation, shown in the second column of Table 5.1. Based on the existing DFP, the components that are used to perform the functions are also included in Table 5.1.

To construct the overall functional diagram, the individual functions in Table 5.1 are connected according to their inputs and outputs, and the result is provided in Figure 5.5. In this functional diagram, the labels of information flows are omitted for simplicity, while the labels of material and energy flows are the same as those in Table 5.1. Then, this functional diagram can be viewed as an "exploded" view of the functional black box in Figure 5.3.

In addition, based on Table 5.1, the *FC* matrix of the DFP can be constructed, and it is provided in Equation (5.2). To illustrate, we can check f_1, which is the first row of the *FC* matrix. This row shows that f_1 is related to c_1 and c_2, which corresponds to the information in Table 5.1 (i.e., diaphragm (c_1) and clamp (c_2) are used for "f_1: import prepreg").

$$FC = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.2}$$

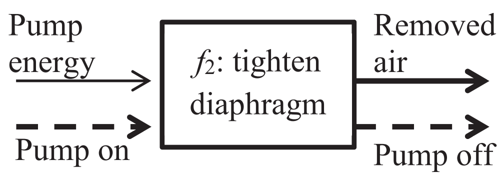
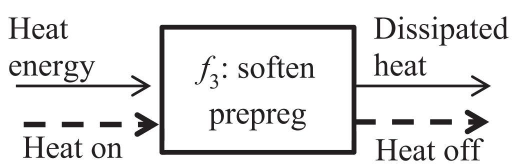
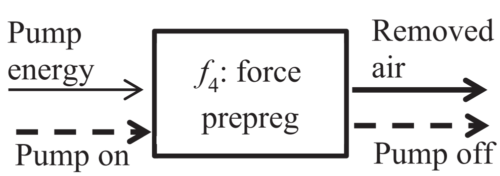
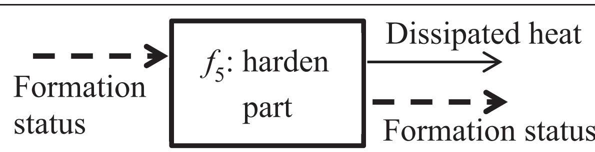
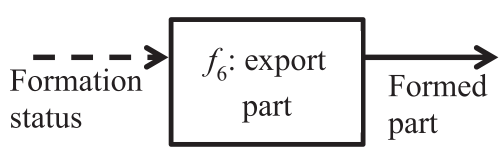
In quality planning, it is intended to construct two matrices: *RM* and *MC*. In the context of eco-design, suppose that the engineers want to reduce energy use and processing time in the DFP. Accordingly, two eco-design requirements (r_1 and r_2) and metrics (m_1 and m_2) are proposed below, along with the *RM* matrix in Equation (5.3).

1. r_1: Less energy use
2. r_2: Less processing time
3. m_1: Energy consumption (in kWh)
4. m_2: Processing time (in minutes)

$$RM = \begin{bmatrix} 9 & 3 \\ 3 & 9 \end{bmatrix} \tag{5.3}$$

In this *RM*, $rm_{11} = rm_{22} = 9$ for the direct measure of energy and processing time. Then we have rm_{12} and $rm_{21} = 3$ since longer processing time implies more energy use (and vice versa). Notably, we do not list all requirements and metrics that are involved in a typical DFP. As we try to focus on eco-design, only the relevant requirements and metrics are listed for highlighting the product "hotspot" for eco-design improvement.

Table 5.1. Functional analysis of DFP

Procedure of DFP	Graphical representation of functions	Components
Put the prepreg between two diaphragms. Clamp the diaphragms.		c_1: diaphragm c_2: clamp
Remove air between diaphragms		c_3: pump 1 c_4: tube
Heat the prepreg		c_1: diaphragm c_5: steel-coil heater
Remove air in the mold		c_1: diaphragm c_4: tube c_6: pump 2 c_7: mold c_8: vacuum box
Cool the mold and remove the formed part	 	c_1: diaphragm c_2: clamp c_7: mold c_8: vacuum box

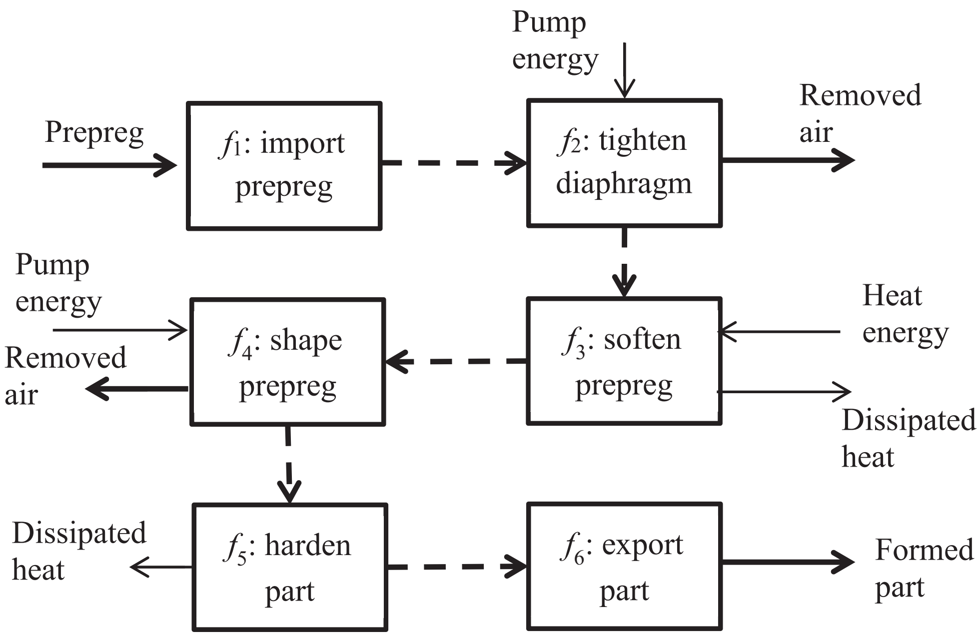


Figure 5.5. Overall functional diagram of DFP

Afterwards, *MC* is developed based on the analysis of the existing DFP, and this *MC* matrix is provided in Equation (5.4). The matrix entries with the value of "9" indicate that the steel-coil heater has the strongest influence towards the energy use and processing time. Since the pumps (c_3 and c_6) also consume energy (not as much as a heater though), we have $mc_{13} = mc_{16} = 3$. Also, since the mold (c_7) can affect the dissipation of heat, it can impact the processing time (thus, $mc_{27} = 3$). Other matrix entries with the value of "1" indicate that the relevant components can slightly affect the energy use and processing time.

$$MC = \begin{bmatrix} 1 & 0 & 3 & 1 & 9 & 3 & 1 & 1 \\ 0 & 1 & 1 & 0 & 9 & 1 & 3 & 0 \end{bmatrix} \tag{5.4}$$

5.4.2 Concept Generation and Evaluation

After the matrices *RM*, *MC* and *FC* are obtained, the matrix *RF* can be determined using Equation (5.1) to prioritize the functions for eco-design improvement. The resulting *RF* matrix is provided in Equation (5.5). From this *RF*, it is found that the function f_3 (i.e., soften prepreg) has the strongest influence for achieving r_1 and r_2 (i.e., $rf_{13} = 117$ and $rf_{23} = 111$). Comparatively, f_1 and f_6 (i.e., import prepreg and export part) are not so important for r_1 and r_2, and thus, they are not included in the morphological chart for concept generation.

$$RF = \begin{bmatrix} 12 & 39 & 117 & 75 & 27 & 12 \\ 12 & 21 & 111 & 57 & 33 & 12 \end{bmatrix} \tag{5.5}$$

Accordingly, the morphological chart is built in Figure 5.6 with the descending priority of functions based on the resulting *RF*. Since f_3 has the strongest influence, the focus is on this function for generating new design ideas. First of all, while heating is unavoidable to soften the prepreg, it is noted that the ceramic-coil heater can potentially have better heating efficiency. Also, in view of the heating strategy, it may be efficient to adopt some "preheat" strategy for the subsequent softening process. As one result, it is proposed to preheat the mold using an electric heater. Without introducing a new heater, it is noted that f_3 has an output "dissipated heat" (as well as f_5), and it is proposed to use the dissipated heat to preheat prepreg 2 during the heating process of the first prepreg. The dissipated heat can accordingly be employed for the all required materials.

Other design ideas are also generated by checking other functions (i.e., f_4, f_2 and f_5). Since these functions have less impact to r_1 and r_2, we can choose to devote less effort for brainstorming new ideas for these functions. Here, the essence of the proposed eco-design method is to prioritize the design functions so that the engineers can choose to devote their design efforts accordingly.

After developing the morphological chart, two design concepts are proposed accordingly. First of all, as the ceramic-coil heater and the single pump with rewired tube are quite feasible in practice, these two solution concepts are used for the two concepts. To differentiate, the first concept (namely, concept '*x*') adopts the electric heater concept to preheat the mold. Alternately, the second concept (namely, concept '*y*') adopts the dissipated heat to preheat the prepreg 2 using a new fan. Both concepts '*x*' and '*y*' are illustrated in Figures 5.7 and 5.8, respectively.

Function	Possible solutions			
	Existing solutions	Solution 1	Solution 2	Solution 3
f_3: soften prepreg	Steel-coil heater	Ceramic-coil heater	Preheat mold using electric heater	Preheat prepreg 2 using dissipated heat
f_4: shape prepreg	Two pumps	Single pump with rewired tube		
f_2: tighten diaphragm	Two pumps	Single pump with rewired tube		
f_5: harden part	Room temperature	Fan		

Figure 5.6. Morphological chart of the DFP

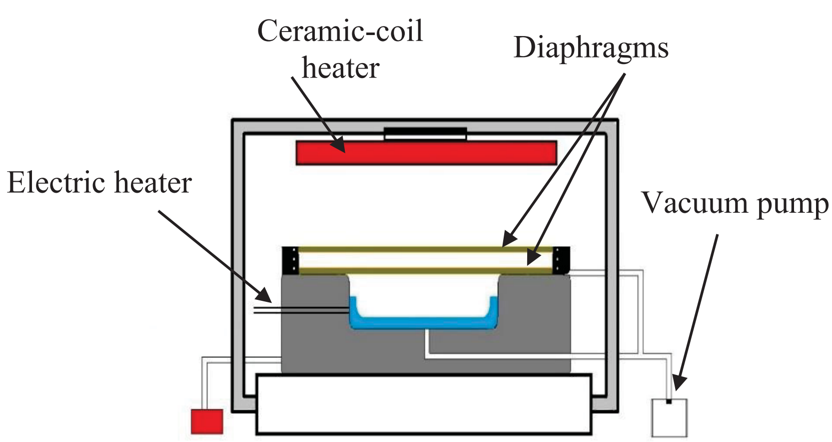


Figure 5.7. Design concept '*x*' of the DFP

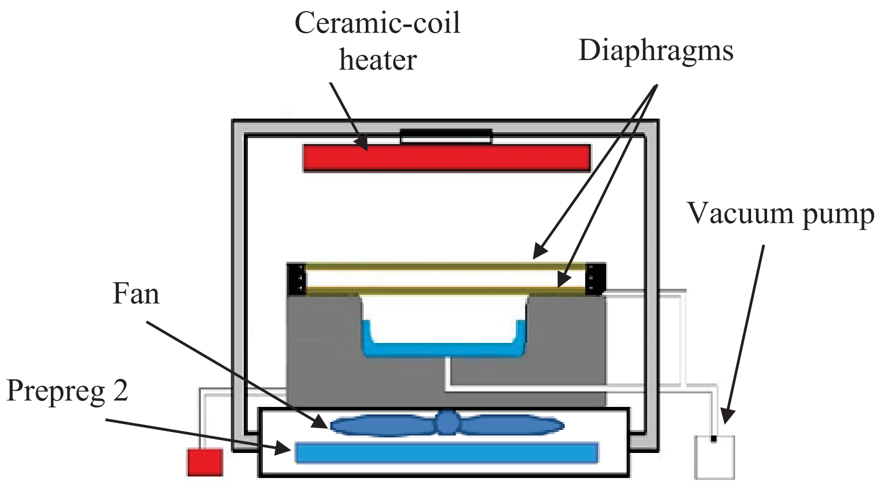


Figure 5.8. Design concept '*y*' of the DFP

To evaluate design concepts, two metrics defined earliers are used: energy use (m_1) and processing time (m_2). To estimate the energy use, first the power ratings of the components that consume energy should be determined and then approximate their usage times. To estimate the processing time, the time required for achieving the functions from f_2 (i.e., tighten prepreg) to f_5 (i.e., harden part) is checked. The functions of f_1 and f_6 are not considered here since the new concepts should have about the same processing time with the original design in these two functions.

Table 5.2 tabulates the initial analysis. In the column of energy use, the components that consume energy are listed for the original and proposed designs. In the column of processing time, the times of the original design are treated as a benchmark, and the times of concept '*x*' and '*y*' are commented with the note "same" or "shorter".

Table 5.2. Initial analysis of energy use and processing time

	Energy use	Processing time
Original	Consumed by sheet-coil heater and two pumps	Tighten time → soften time → shape time → harden time
Concept ‘*x*’	Consumed by ceramic heater, electric heater, and one pump	Tighten time (same) → soften time (shorter) → shape time (same) → harden time (same)
Concept ‘*y*’	Consumed by ceramic heat, fan, and one pump	Tighten time (same) → soften time (shorter) → shape time (same) → harden time (shorter)

To quantify the estimation, the power ratings and run times of the components in the DFP are recorded in Table 5.3. This table has two parts. The first part records the power ratings and run times of existing components, while the second part (the rows with gray color) provides the estimations related to the proposed components in concepts ‘*x*’ and ‘*y*’. Then, the energy use for concept evaluation can be determined by multiplying power rating with run time.

Table 5.4 records the energy use and processing time of the original design and concepts ‘*x*’ & ‘*y*’. First of all, the energy use is addressed by working on the function f_3 via the ceramic-coil heater (for less power rating) and the preheat strategy (for less heating time). By using only one pump (that has higher power rating), concepts ‘*x*’ and ‘*y*’ require more energy for f_2 (tighten diaphgram). Regarding the processing time, the fan is expected to reduce about 30% of the hardening time, which becomes 21 minutes in concept ‘*y*’. The tradeoff, of course, is the extra energy use for the fan. Since fans generally have much lower power ratings (as compared to heating components), they represent a good option for engineers to reduce the processing time.

Table 5.3. Information for estimating energy use and processing time

Components that consume power	Power rating	Run time	Comments
Steel-coil heater	6.0 kW	15.0 min	Used in original (soften prepreg)
Pump 1	0.56 kW	7.8 min	Used in original (tighten prepreg)
Pump 2	0.74 kW	9.6 min	Used in original and concepts ‘*x*’ & ‘*y*’ for shape prepreg
Pump 2	0.74 kW	7.8 min	Concepts ‘*x*’ & ‘*y*’: tighten prepreg
Ceramic-coil heater	5.7 kW	12.0 min	Used in concept ‘*x*’, shorter time due to preheat mold
Ceramic-coil heater	5.7 kW	14.0 min	Used in concept ‘*y*’, shorter time due to preheat prepreg 2
Electric heater	2.0 kW	5.0 min	Used in concept ‘*x*’, preheat mold during tighten prepreg
Fan	0.05 kW	21 min	Used in concept ‘*y*’, cool mold during shape prepreg

Table 5.4. Comparison of metrics of new design concepts

	Original		Concept ‘*x*’		Concept ‘*y*’	
	Energy	Time	Energy	Time	Energy	Time
f_2: tighten diaphragm	0.073 kWh	7.8 min	0.096 kWh	7.8 min	0.096 kWh	7.8 min
f_3: soften prepreg	1.5 kWh	15.0 min	1.3 kWh	12.0 min	1.4 kWh	14.0 min
f_4: shape prepreg	0.12 kWh	9.6 min	0.12 kWh	9.6 min	0.12 kWh	9.6 min
f_5: harden part	0 kWh	30.0 min	0 kWh	30.0 min	0.018 kWh	21.0 min
Total	1.693 kWh	62.4 min	1.516 kWh	59.4 min	1.634 kWh	52.4 min

5.4.3 Discussion

By reflecting on the new design concepts ‘*x*’ and ‘*y*’, this section is intended to examine how the proposed method can actually support the generation of new concepts for eco-design improvement. By checking Table 5.4, it is observed that both concepts ‘*x*’ and ‘*y*’ can potentially reduce the energy use and processing time of the existing DFP. This result is mainly based on three design techniques, which listed and commented below.

- Use a more efficient heater for “soften prepreg”. This design technique is rather “obvious”, and the energy-saving result is quite predictable.
- Adopt a “preheat” strategy. This design technique is less obvious as preheat is not one of the original functions. Yet, by realizing that a fixed amount of energy is more or less required to the function “soften prepreg”, the energy consumption tends to be explored beyond the original heater, and thus the preheat strategy emerges in the concept generation process.
- Adopt a fan. This design technique emerges when the possible solutions are considered for the function “harden part” (see the morphological chart in Figure 5.6). This idea does not look interesting preliminarily until the dissipated heat is observed in the functional diagram in Figure 5.5. Combining the idea of preheat, the fan can actually redistribute the dissipated heat for some useful purpose.

As discussed here, the ideas of “preheat” and “fan” are obtained based on the reasoning process within the proposed methodology. Arguably, some talented engineers may come up with some similar eco-design ideas without using the proposed methodology. Yet, in reality, we cannot rely on the “light-bulb” moments from few talented engineers entirely. Therefore, the proposed methodology is intended to support engineers to organize design information (in terms of matrices) and direct their design efforts systematically. In this way, it is expected that new eco-design ideas can emerge steadily as one kind of continual improvement emphasized in six-sigma management (McCarty et al., 2011).

5.5 Summary

During the course of the development of the eco-design methodology, it is intended to organize the research materials to provide a balance between methodical complexity and applicability. As Chapters 3 and 4 present a comprehensive view of the methodology, this chapter employs a manufacturing process to demonstrate the method's applicability. Beyond concept generation, the next chapter will focus on the method concerning concept selection in the presence of design uncertainty. The above presented work is submitted to a refereed journal[4] for publication.

[4] International Journal of Sustainable Engineering, 2015

Chapter 6 : Trapezoidal Fuzzy Numbers for Eco-Design Assessments

After generating multiple design concepts for eco-design improvement, it is common for engineers to assess these concepts for further developments. Section 4.2 has introduced the Pugh selection method as a simple approach for concept selection. In this chapter, the approach by trapezoidal fuzzy numbers is proposed to formally address the uncertainty information in eco-design concept selection. As a recall from the literature review in Chapter 2, the uncertainty in life-cycle assessment (LCA) is usually addressed by the Monte Carlo simulation. Yet, since the uncertainty due to design judgments is not quite stochastic by nature (Wood et al., 1992), the fuzzy set approach is adapted in this study. Particularly, the trapezoid fuzzy numbers (TrFN) are used. TrFN is a more general form than a triangular fuzzy number, and it has not been often applied in the context of eco-design concept selection. This chapter is organized as follows. The context of eco-design assessments is first described, with the introduction of TrFN to capture imprecise design information and fuzzy arithmetic. After that, the centroid concept is applied to model different views of imprecision (i.e., pessimistic, balanced and optimistic) associated in fuzzy assessment. Accordingly, a decision scheme is developed for assessing different design concepts and suggesting the potential areas of a design concept to reduce environmental impacts. In an application, a coffee maker example in the earlier chapters is used to demonstrate the developed method.

6.1 Eco-Design Assessments and Fuzzy Arithmetic

6.1.1 Eco-Indicators and Life Cycle Assessment (LCA)

The review of eco-indicators is explained in Chapter 2, Section 2.4. In this study Eco-indicator 99 is employed to assess environmental impacts of a product. For recall, engineers are required to gather some engineering information such as amounts of materials (in kg), energy consumption (in

KWh) and the amounts of disposed wastes (in kg) to improve existing designs. These engineering quantities have different units, it is common for life cycle assessment (LCA) to involve some standard environmental indicators (or Eco-indicators) to aggregate these quantities for overall comparisons (Ashby, 2009; Fiksel, 2009). In this thesis, the Eco-indicator 99 is chosen to evaluate the overall fuzzy environmental impact of design information. Each eco-indicator can be viewed as a weight reflecting an environmental impact associated with a particular engineering quantity.

6.1.2 Eco-Design Assessment Context

In eco-design, it is intended to modify an existing product for the purpose of reducing environmental impacts. During the process of design modifications, conceptual design is carried to generate design concepts, and some design tools can be used at this stage such as functional decomposition and morphological analysis (Otto and Wood, 2001). Design concepts here can be viewed as the possible approaches to reduce environmental impacts associated with the existing product. In the environmental assessment, it is supposed that the engineers have developed a set of design concepts, symbolized as $D = \{x, y, z \ldots\}$.

Given a set of design concepts, the role of eco-design assessment is to evaluate these design concepts and indicate which one has the best potentials for reducing environmental impacts. To evaluate each design concept objectively, a set of engineering quantities is used such as the amounts of materials, energy consumption and the amounts of disposed wastes. In such a way, the design concepts are generally compared in view of some quantifiable data such as material usages and energy consumptions. In practice, the assessment of these engineering quantities facilitates to the use of eco-indicators.

Let $E = \{a, b, c\ldots\}$ be the set of engineering quantities and $a(x)$ be the value of quantity 'a' associated with concept 'x'. To clarify the use of symbols, Table 6.1 shows an example of three design concepts evaluated with three engineering quantities.

From Table 6.1, to reduce environmental impacts, it is desirable to have less material usage, energy consumption and solid waste. In this view, there exist some performance trade-offs among the three design concepts. For instance, concept 'x' has the best (or minimal) material usage (i.e., quantity 'a') but the worst (or most) energy consumption (i.e., quantity 'b'). As these engineering quantities have different units, Eco-indicator 99 is used to aggregate these quantities for overall comparisons. Each eco-indicator can be viewed as a weight quantifying an environmental impact associated with a particular engineering quantity. Let $F = \{i_a, i_b, i_c\ldots\}$ be the set of eco-indicators, where i_a is the eco-indicator of the quantity 'a'. Then, the overall impact assessment of concept 'x', denoted as $I(x)$, can be evaluated via the following formulation.

$$I(x) = a(x)*i_a + b(x)*i_b + c(x)*i_c + \ldots + j(x)*i_j + \ldots \text{ where } j \in E \quad (6.1)$$

If the values of engineering quantities (e.g., $a(x)$) are "crisp", we just need to compare the overall assessment values (e.g., $I(x)$ versus $I(y)$), and it is quite a trivial task. However, at the stage of conceptual design, engineers typically do not have precise values of engineering quantities, which should only be available after the stage of detailed design. The next sub-section will discuss the use of trapezoidal fuzzy numbers for design estimation.

Table 6.1. An example of comparing design concepts with engineering quantities

	Quantity 'a' (Material usage)	Quantity 'b' (Energy consumption)	Quantity 'c' (Solid waste)
Concept 'x'	$a(x)$ = 10.0 kg	$b(x)$ = 1100 KWh	$c(x)$ = 2.4 kg
Concept 'y'	$a(y)$ = 10.5 kg	$b(y)$ = 1050 KWh	$c(y)$ = 2.3 kg
Concept 'z'	$a(z)$ = 11.2 kg	$b(z)$ = 1020 KWh	$c(z)$ = 2.9 kg

6.1.3 Design Estimation via Trapezoidal Fuzzy Numbers

When designers plan to improve an existing product for reducing environmental impacts, they should have some design information about the existing product. Based on the existing design information and engineers expertise, it is assumed that designers can estimate certain design quantities related to the proposed design concepts (e.g., the estimated weight of aluminum to be used in the product). In this research, the engineers' estimation is modeled via trapezoidal fuzzy numbers (TrFN). Particularly, TrFN is intended to capture two aspects of estimation: (1) the range of typical values and (2) the lower and upper bounds. Typical values represent the values of engineering quantities that are likely to take place if the design concept is developed. The lower and upper bounds represent the optimistic and pessimistic estimations of engineering quantities, respectively.

Using the example of Table 6.1, while the material usage of concept '*x*' is stated as 10.0 kg (i.e., $a(x)$ = 10.0 kg), engineers may consider that the actual value can be between 9.5 kg and 11.0 kg, and this becomes the range of typical values. Moreover, engineers can also consider that the best and worst cases to reduce the material usage of concept '*x*' can go beyond the range of 9.5-11.0 kg. Then, the lower and upper bounds (e.g., 8.5 kg and 13.0 kg) can be specified to reflect the best and worst cases in the engineers' estimation.

In this research, the estimation of engineering quantities (symbolized as a) is represented via trapezoidal fuzzy numbers (TrFN). Let Fa be the fuzzy number of quantity 'a'. Each TrFN is identified by a quadruple, i.e., $Fa = (a_1, a_2, a_3, a_4)$, in which a_1 represents the lower bound, a_2 to a_3 the range of typical values, and a_4 the upper bound. The membership function (donated as $\mu(a)$) of a TrFN reflects the likelihood of the actual value of the quantity a after detailed design, and it is formulated in Equation (6.2) as follows. Figure 6.1 illustrates the plot of the membership function.

In our consideration, the advantage of using TrFN is its generality to express uncertain information. First of all, interval values have been generally used in design and manufacturing to express uncertain information (e.g., tolerance). Fuzzy numbers are actually a generalization of interval values (Lee, 2006). For example, if we set $a_1 = a_2$ and $a_3 = a_4$, a TrFN is operationally equivalent to an interval. Furthermore, a TrFN can also be used to represent a triangular fuzzy number (by setting $a_2 = a_3$) and a crisp number (by setting $a_1 = a_2 = a_3 = a_4$). At this point, engineers are not strictly required to specify four different values (i.e., a_1 to a_4) for each engineering quantity. Depending on the situations, engineers can specify engineering quantities in terms of crisp values, intervals, or triangular fuzzy numbers under the same TrFN formulation.

$$\begin{cases} 0 & a < a_1 \\ \frac{a - a_1}{a_2 - a_1} & a_1 \leq a < a_2 \\ 1 & a_2 \leq a < a_3 \\ \frac{a - a_4}{a_3 - a_4} & a_3 \leq a \leq a_4 \\ 0 & a > a_4 \end{cases} \tag{6.2}$$

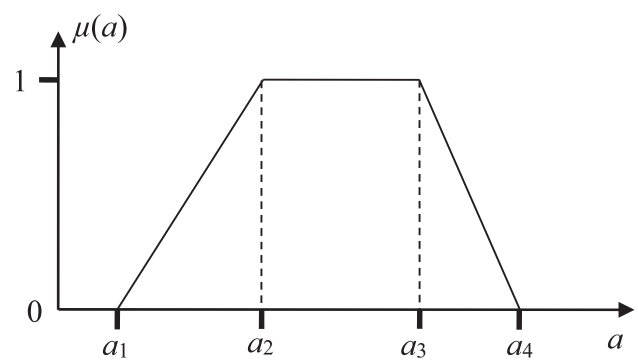


Figure 6.1. Illustration of a trapezoidal fuzzy number

6.1.4 Aggregation of TrFN

After defining TrFN in the previous section, the task of this sub-section is to generalize the overall impact assessment of concept 'x' formulated in Equation (6.1) by replacing each engineering quantity (e.g., $a(x)$) with fuzzy number (e.g., Fa). Two arithmetic operations are carried out in Equation (6.1): addition and multiplication with a scalar. Fortunately, fuzzy numbers after these two types of arithmetic operations remain a fuzzy number (Lee, 2006), and this result can stay the analysis process relatively simple. Let w be a scalar, and $\oplus$ and $\otimes$ be fuzzy addition and multiplication, respectively. Equations (6.3) and (6.4) show the formulations for adding TrFN and multiplying a TrFN with a scalar.

$$\begin{aligned} Fa \oplus Fb &= (a_1, a_2, a_3, a_4) \oplus (b_1, b_2, b_3, b_4) \\ &= (a_1+b_1, a_2+b_2, a_3+b_3, a_4+b_4) \end{aligned} \tag{6.3}$$

$$\begin{aligned} w \otimes Fa &= w \otimes (a_1, a_2, a_3, a_4) \\ &= (w*a_1, w*a_2, w*a_3, w*a_4) \end{aligned} \tag{6.4}$$

Let $FI(x)$ be the TrFN that corresponds to $I(x)$ formulated in (6.1), and $Fa(x)$ be the TrFN of quantity 'a' of concept 'x'. At this point, the fuzziness of $FI(x)$ comes from the estimation of engineering quantities (e.g., $a(x)$) via TrFNs (e.g., $Fa(x)$), and the formulation of $FI(x)$ is provided as follows.

$$FI(x) = Fa(x) \otimes i_a \oplus Fb(x) \otimes i_b \oplus Fc(x) \otimes i_c \oplus \ldots \oplus Fj(x) \otimes i_j \oplus \ldots \text{ where } j \in E \tag{6.5}$$

Note that the fuzzy number $Fa(x)$ can be represented by a quadruple $(a_1(x), a_2(x), a_3(x), a_4(x))$. As $Fa(x)$ is a TrFN and i_a is a scalar (eco-indicator), the resulting $FI(x)$ is also a TrFN. Based on

Equations (6.3) and (6.4), the overall fuzzy impact of the design concept 'x' can be expressed by a TrFN with the quadruple ($I_1(x)$, $I_2(x)$, $I_3(x)$, $I_4(x)$), which can be evaluated as follows.

$$FI(x) = \left(I_1(x), I_2(x), I_3(x), I_4(x)\right)$$

$$= \left(\textstyle\sum_{a \in E} a_1(x) * i_a, \sum_{a \in E} a_2(x) * i_a, \sum_{a \in E} a_3(x) * i_a, \sum_{a \in E} a_4(x) * i_a\right) \qquad (6.6)$$

While Equation (6.6) represents the overall environmental assessment of concept 'x', the next sub-section will discuss how to use this TrFN for decision making.

6.2 Decision Analysis Based on TrFN

6.2.1 Centroids of TrFN

As ranking a set of crisp numbers is elementary, ranking fuzzy numbers is not a trivial task, and various approaches have been proposed such as maximizing and minimizing sets (Chen, 1985), integral value (Liou and Wang, 1992), and centroid (Cheng, 1998). In our view, the difficulty in ranking fuzzy numbers is due to the uncertainty presented in a fuzzy number. For example, if a fuzzy number $Fa = (a_1, a_2, a_3, a_4)$ has higher a_2 and a_3 (i.e., higher typical values) but lower a_1 (i.e., larger uncertainty) than another fuzzy number Fb, we cannot immediately conclude that Fa is greater than Fb.

Therefore, we adapt the concepts that explicitly incorporate the uncertainty aspect of a fuzzy number such as the index of optimism (Facchinetti et al., 1998; Liou and Wang, 1992) and the coefficient of variation (Cheng, 1998). In addition, we will use the centroid formulations which have been applied (Wang et al., 2006) to represent the center point of a trapezoidal fuzzy number. Let ($x_c(Fa)$, $y_c(Fa)$) be the centroid point of the trapezoidal fuzzy number $Fa = (a_1, a_2, a_3, a_4)$, and the formulations are provided as follows.

$$x_c(Fa) = \frac{1}{3}\left[a_1 + a_2 + a_3 + a_4 - \frac{a_3 a_4 - a_1 a_2}{a_3 + a_4 - a_1 - a_2}\right] \tag{6.7}$$

$$y_c(Fa) = \frac{1}{3}\left[1 + \frac{a_3 - a_2}{a_3 + a_4 - a_1 - a_2}\right] \tag{6.8}$$

Based on the centroid formulations, three types of measures are developed in this research based on the notion from (Facchinetti et al., 1998).

- Balanced: A balanced centroid is the actual geometric centroid of a trapezoid, and Equations (6.7) and (6.8) are used to compute the balanced centroid point.
- Pessimistic: A pessimistic view focuses on the possibility of poor results for ranking analysis. In this study, high values will lead to high impact measures, implying poor results. Thus, the pessimistic measure focuses on the right-hand side of TrFN. Particularly, we draw a vertical line between a_2 and a_3 to define the right-hand side (illustrated in Figure 6.2), which essentially represents another TrFN as $((a_2+a_3)/2, (a_2+a_3)/2, a_3, a_4)$. Let $(x_p(Fa), y_p(Fa))$ be the pessimistic point of TrFN: $Fa = (a_1, a_2, a_3, a_4)$. Based on Equations (6.7) and (6.8), the formulations of the pessimistic measure are derived as follows.

$$x_p(Fa) = \frac{1}{3}\left[a_2 + 2a_3 + a_4 - \frac{4a_3 a_4 - (a_2 + a_3)^2}{4a_4 - 4a_2}\right] \tag{6.9}$$

$$y_p(Fa) = \frac{1}{3}\left[1 + \frac{a_3 - a_2}{2a_4 - 2a_2}\right] \tag{6.10}$$

- Optimistic: An optimistic view focuses on the possibility of good results for ranking analysis. In contrast, the optimistic measure focuses on the left-hand side of TrFN, which is expressed as (a_1, a_2, $(a_2+a_3)/2$, $(a_2+a_3)/2$). Let ($x_o(Fa)$, $y_o(Fa)$) be the optimistic point of TrFN: $Fa = (a_1, a_2, a_3, a_4)$. Based on Equations (6.7) and (6.8), the formulations of the optimistic measure are derived as follows.

$$x_o(Fa) = \frac{1}{3}\left[a_1 + 2a_2 + a_3 - \frac{(a_2+a_3)^2 - 4a_1a_2}{4a_3 - 4a_1}\right] \tag{6.11}$$

$$y_o(Fa) = \frac{1}{3}\left[1 + \frac{a_3 - a_2}{2a_3 - 2a_1}\right] \tag{6.12}$$

Figure 6.2 illustrates the positions of balanced, pessimistic and optimistic centroids of a TrFN. Notably, the pessimistic centroid has the focus on a_2, a_3 and a_4, while the optimistic centroid focuses on a_1, a_2 and a_3. This explains the relative positions of these centroids.

6.2.2 Ranking Analysis

For ranking analysis, the distances are determined from the origin to the three types of centroid points, denoted as d_c (balanced), d_p (pessimistic) and d_o (optimistic), which formulations are provided as follows. It should be noted that $d_p \geq d_c \geq d_o$.

$$d_c(Fa) = \sqrt{x_c(Fa)^2 + y_c(Fa)^2} \tag{6.13}$$

$$d_p(Fa) = \sqrt{x_p(Fa)^2 + y_p(Fa)^2} \tag{6.14}$$

$$d_o(Fa) = \sqrt{x_o(Fa)^2 + y_o(Fa)^2} \tag{6.15}$$

In this work, the balanced, pessimistic and optimistic distances are applied to the environmental fuzzy assessment of design concept 'x', i.e., $FI(x)$ in Equation (6.6). Then, these determined distances are compared with the environmental impact of the original design. Since the original design is considered as "existing" design (in contrast to "non-existing" design concept), the environmental impact of the original design is a crisp number, denoted as *ori* in this study. Let d_{ori} be the distance from the origin to the "imaginary" centroid of the crisp number *ori*, and it is formulated as follows.

$$d_{ori} = \sqrt{ori^2 + 0.5^2} \tag{6.16}$$

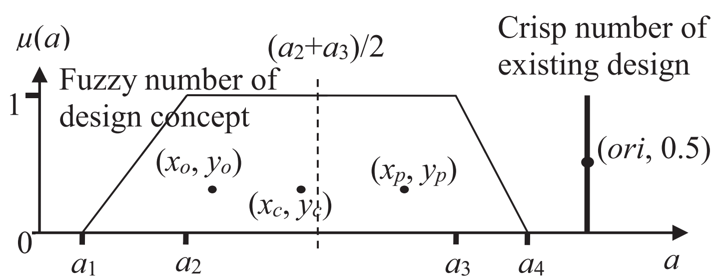


Figure 6.2. Illustration of the points to determine d_c, d_p, d_o and d_{ori}

Figure 6.2 illustrates the positions of the points that are used to determine d_c, d_p, d_o and d_{ori}. As a recall, longer distances imply higher environmental impacts estimated by eco-indicators. The ranking analysis is then based on the comparison among d_c, d_p, d_o and d_{ori}. Two ranking approaches are suggested as follows to accommodate uncertainty information.

- Comparison with original design (COD): The proposed concept is compared with the original design to examine whether the concept has real potential to reduce environmental impacts from the original design.

- Comparison among multiple concepts (CMC): Several design concepts are compared to examine which one has better potential to reduce environmental impacts subject to some risks.

In the COD analysis, the strategy is to compare d_{ori} (as a crisp number) with respect to three distances associated with the design concept (i.e., d_c, d_p and d_o). Given the design concept '*x*', four cases are derived below to compare the design concept '*x*' with the original design.

- Case 1: $d_{ori} \geq d_p(FI(x)) \geq d_c(FI(x)) \geq d_o(FI(x))$. This case shows that even the pessimistic case of '*x*' has a lower environmental impact than the original design. Thus, we consider that the design concept '*x*' is promising towards the reduction of environmental impacts as compared to the original design. As a side note, Figure 6.2 illustrates one situation of this case.
- Case 2: $d_p(FI(x)) \geq d_{ori} \geq d_c(FI(x)) \geq d_o(FI(x))$. This case shows that the original design has a lower impact than the pessimistic case but the balanced and optimistic cases of '*x*' are better than the original design. Then, we can judge that the design concept is generally good. Yet, the engineers should check and improve the upper impact bounds in view of the engineering quantities in order to minimize the risk of the pessimistic aspect of the design concept.
- Case 3: $d_p(FI(x)) \geq d_c(FI(x)) \geq d_{ori} \geq d_o(FI(x))$. This case shows that only the optimistic case of '*x*' has a lower environmental impact than the original design. Thus, we consider that the design concept '*x*' is not quite promising. It is suggested that the engineers should considerably improve the typical values (e.g., a_2 and a_3) of the engineering quantities for the reduction of environmental impacts. If it cannot be done favorably, the engineers should re-consider other approaches for environmental improvements.
- Case 4: $d_p(FI(x)) \geq d_c(FI(x)) \geq d_o(FI(x)) \geq d_{ori}$. This case shows even the optimistic case of '*x*' has a higher environmental impact than the original design. Thus, the design concept '*x*'

should not be further developed for environmental improvements of the original design. The suggestion is that, the engineers should devote more resources on other design concepts.

While the multiple design concepts are obtained, the CMC analysis is intended to compare various concepts in view of d_c, d_p and d_o. The choice of these distances for comparisons is based on the risks that the company is willing to take during product development. Three situations are listed and discussed below.

- Neutral risk: d_c (i.e., balanced centroid) is used for comparing design concepts.
- Low risk: When the company only wants minimum risk due to the lead time pressure and limited resources, the comparison based on d_p (i.e., pessimistic centroid) is suggested to compare different design concepts.
- High risk: If the company is willing to take higher risk for innovative concepts with adequate resources, the concept comparison based on d_o (i.e., optimistic centroid) is suggested.

In sum, while typical decision analysis usually involves the formulation of a single index to rank design concepts, the COD and CMC analyses have three indices (i.e., d_c, d_p and d_o) for each concept for comparisons. This approach allows more information associated with uncertainty for engineers to decide on the concepts subject to their specific circumstances. In this view, both COD and CMC analyses are simply suggestions for comparisons using d_c, d_p and d_o. Engineers can develop their own approaches to compare design concepts using d_c, d_p and d_o as the uncertainty notion behind d_c, d_p and d_o is not difficult to understand. The next sub-section discusses the procedure that can guide the engineers to use the fuzzy impact assessment methodology.

6.3 Procedure for Eco-Design Assessments

Based on the investigation presented in Sections 6.1 and 6.2, this section provides a step-by-step procedure to perform eco-design assessment in a systematical way. The procedure consists of four methodical steps, which are described as follows.

- Step 1: Collection of the Information of Engineering Quantities

  Engineers are asked to fill in some approximate design information related to the design concepts. Under the environmental considerations, specific information mainly includes the amounts of major materials, energy consumption during use, and the amounts of disposed wastes. Note that this information conveys quantifiable measures. In this aspect, the notion of approximation is to ask engineers for the ranges of typical values of these quantities as well as their possible upper and lower bounds. It can be argued that engineers should have some rough ideas towards these engineering measures during conceptual design (particularly based on past design experience). Their major limitation is that the values of these quantities may not be very precise. Thus, the upper and lower bounds are there to capture the imprecision. Figure 6.3 shows a sample form that engineers can fill in to capture the conceptual design information.

- Step 2: Evaluation of Fuzzy Impact Assessments

  After collecting the information of uncertain engineering quantities, engineers are asked to employ one environmental assessment standard (e.g., Eco-indicator 99) to find the values of eco-indicators $F = \{i_a, i_b, i_c..\}$. Then, Equation (6.6) is used to evaluate the overall fuzzy environmental impact for each design concept.

- Step 3: Ranking Measures of Design Concepts

After obtaining the overall fuzzy impacts for design concepts, determine the corresponding balanced, pessimistic and optimistic distances of environmental impacts using Equation (6.13) to (6.15) for each design concept.

- Step 4: Ranking Analysis and Suggestions

  Note that each design concept comes with three distances: balanced (d_c), pessimistic (d_p) and optimistic (d_o). To examine the environmental design improvement, first the environmental impact value of the original design (i.e., *ori* and d_{ori}) should be determined. Then, compare each design concept with d_{ori} based on the COD analysis to determine which of the four cases that the design concept belongs to. When multiple concepts are represented, the CMC analysis is applied to select the concept(s) subject to the risk level that the company is willing to take.

	Lower bound (a_1)	Range of typical values ($a_2 - a_3$)	Upper bound (a_4)
Material usage (kg)			
Energy consumption (KWh)			
Solid waste (kg)			

Figure 6.3. A sample form to collect the information of engineering quantities

6.4 Example: Coffee Maker

6.4.1 Information of Existing Design

To demonstrate the proposed method, a household coffee maker which is common in the market has been used. After product decomposition, various components are identified, and they are shown in Figure 6.4. To assess the environmental impacts, the analysis in the design manual and the methodology report of Eco-indicator 99 (Goedkoop et al., 2000; Goedkoop and Spriensma, 2001) are mainly applied. Firstly, the major materials used in the coffee-maker components are identified and weighted. Table 6.2 lists four major types of materials of the actual product shown in Figure 6.4.

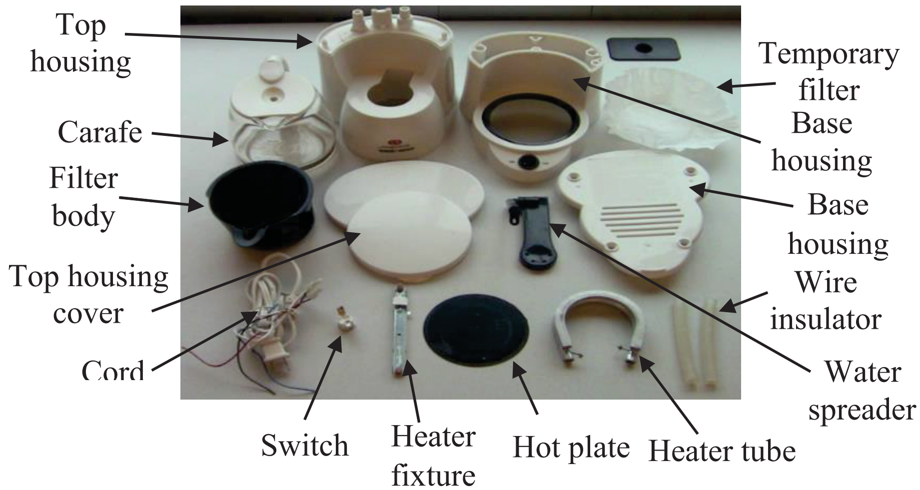


Figure 6.4. Disassembly of the coffee maker

Table 6.2. Major materials in a coffee maker

Material	Related Components	Weight
Polystyrene	Filter body, housing and cover, carafe cover, water spreader	0.56 kg
Aluminum	Heater tube	0.082 kg
Steel	Hot plate , heater fixture	0.075 kg
Glass	Carafe	0.22 kg

Secondly, it is assumed that the useful life of a coffee maker is three years. Also, it is operated two times with total of 0.5 hour per day. The coffee maker uses 600 watts, and thus the electricity consumption over three years is equal to 600×0.5×365×3 = 328.5 kWh. The weight of each filter paper is measured as 0.89 grams, and the total weight of filter papers over three years is equal to 0.89×2×365×3 = 1.95 kg.

In view of LCA and the use of Eco-indicator 99, we focus on four categories of environmental impacts: material production, processing, use and disposal. In the Canadian context (Statistics Canada, 2005), it can be assumed that the coffee maker will be landfilled after its useful life. Table 6.3 shows the values of eco-indicators and the amounts for each category to evaluate the environmental impacts of the existing coffee maker.

Table 6.3. Environmental assessment of the existing product

		Eco-indicator	Amount	Impact score
Material production	Polystyrene (PS)	360 (mPt / kg)	0.56 kg	201.6 mPt
	Aluminum (Al)	780 (mPt / kg)	0.082 kg	63.96 mPt
	Steel	86 (mPt / kg)	0.075 kg	6.45 mPt
	Glass	58 (mPt / kg)	0.22 kg	12.76 mPt
Processing	Injection moulding (PS)	21 (mPt / kg)	0.56 kg	11.76 mPt
	Extrusion (Al)	72 (mPt / kg)	0.082 kg	5.904 mPt
	Sheet (steel)	30 (mPt / kg)	0.075 kg	2.25 mPt
Use	Electricity	37 (mPt / kWh)	328.5kWh	12154.5 mPt
	Filter paper	96 (mPt / kg)	1.95 kg	187.2 mPt
Disposal (landfill)	Polystyrene (PS)	4.1 (mPt / kg)	0.56 kg	2.296 mPt
	Aluminum (Al)	1.4 (mPt / kg)	0.082 kg	0.1148 mPt
	Steel	1.4 (mPt / kg)	0.075 kg	0.105 mPt
	Glass	1.4 (mPt / kg)	0.22 kg	0.308 mPt
	Paper	4.3 (mPt / kg)	3.25 kg	13.975 mPt
			Total	12663 mPt

6.4.2 Proposal of Three Design Concepts

Referring to Goedkoop and Spriensma, (2001) and similar products in the market, three design concepts have been proposed in this study, and they are discussed in the following.

- Concept '*x*': This concept is intended to reduce the electricity consumption by redesigning the heating method. The current design has a single heating source (i.e., aluminum tube) that serves two functions: heating up water and keeping coffee warm. The new design plans to develop two separate heating sources for these two functions, respectively. It is planned to implement precise control of electricity usage (e.g., time of heating water and warming coffee) and better insulation at the machine's bottom to minimize the waste of heat.

- Concept '*y*': This concept is intended to reduce material usage by replacing paper filters with a permanent filter. It is expected that the original housing structure needs to be modified to accommodate the permanent filter.
- Concept '*z*': This concept is intended to reduce the electricity consumption by using an insulated jug instead of the carafe so that the heating function for warming coffee can be removed. To maintain proper coffee temperature in a reasonable time, the insulated jug must have good quality (implying more materials than a carafe).

Given these design concepts, one question is whether they can truly reduce environmental impacts as compared to the existing design. Particularly, each of these concepts implies various levels of trade-offs (e.g., less energy but more material usage). Table 6.4 summarizes the trade-off information and the uncertain levels associated with each design concept.

In practice, engineers may reference Eco-indicator 99 directly to analyze the trade-offs of environmental impacts due to different sources (e.g., 1 kg of glass versus 2 kg of plastics). However, this trade-off analysis is not trivial when multiple sources of environmental impacts are present. Also, the issue of uncertainty incurs additional difficulties. In the next sub-section, the fuzzy eco-design assessment is intended to capture the engineers' judgment of design concepts in terms of engineering quantities and corresponding uncertainties. Then, the decision process is applied to assess whether each design concept has good potential to actually reduce environmental impacts.

Table 6.4. General comparisons of design concepts

	Design intent	Trade-off	Uncertainty
Concept '*x*'	Separate heating sources to reduce electricity consumption	More materials for new heating design	High because this design concept is relatively new
Concept '*y*'	Permanent filter to avoid the use of paper filters	More materials and washing water for permanent filters	Low because similar design can be found in the market
Concept '*z*'	High-quality insulated jug to avoid additional heat for warming coffee	More steel and plastics for jug materials	Medium because existing jugs are not quite satisfactory

6.4.3 An Overview of Eco-Design Fuzzy Assessments

In the assessment process, the procedure in Section 6.3 is followed. At the beginning, engineers are asked to estimate various engineering quantities associated with the proposed design concepts. In this particular case, engineers mainly focus on the estimation of the amounts by referencing Table 6.3 about the information of the existing design. The estimation is expressed via the range of typical values (i.e., a_2 to a_3) and the lower and upper bounds (i.e., a_1 and a_4). The estimation results for concepts '*x*', '*y*' and '*z*' are listed in Table 6.5. As these values are based on design judgments and the knowledge of the coffee maker design, some of them are explained as follows for the verifications by readers.

1. The amounts of polystyrene and steel have increased for new heating design (concept '*x*'), permanent filter (concept '*y*') and new insulted jug (concept '*z*').
2. New heating design in concept '*x*' may require additional aluminum but not in the case of other concepts that use existing heating design.
3. Glass is eliminated in concept '*z*' for not using glass jug. Filter papers are eliminated in concept '*y*' due to the use of the permanent filter.

4. Both concepts '*x*' and '*z*' are intended to reduce electricity consumptions. Yet, concept '*x*' has higher uncertainty on the electricity reduction.
5. The permanent filter in concept '*y*' requires washing water during use. The minimum estimation is to use 2 liters of water for washing two times daily. Then, the three-year consumption is equal to 2×365×3 = 2190 liters (equal to 2190 kg). The maximum is 5 liters. The eco-indicator of washing water is 0.026 mPt / kg.

Based on the information in Table 6.5, the fuzzy environmental impact for each design concept can be evaluated using Equation (6.6). Further, the impact distances based on balanced, pessimistic and optimistic centroids (i.e., d_c, d_p and d_o) can be determined. The corresponding results are summarized in Table 6.6. By referencing the total in Table 6.3, we have d_{ori} = 12663 mPt after applying Equation (6.16).

Table 6.5. Estimation of engineering quantities for each design concept

	Concept '*x*'(separate heat) (a_1, a_2, a_3, a_4)	Concept '*y*' (permanent filter) (a_1, a_2, a_3, a_4)	Concept '*z*' (insulted jug) (a_1, a_2, a_3, a_4)
Polystyrene (kg)	(0.56, 0.65, 0.71, 0.84)	(0.68, 0.75, 0.79, 0.85)	(0.82, 0.85, 0.89, 0.92)
Aluminum (kg)	(0.082, 0.16, 0.17, 0.19)	(0.082, 0.082, 0.082, 0.082)	(0.082, 0.082, 0.082, 0.082)
Steel (kg)	(0.075, 0.15, 0.16, 0.18)	(0.09, 0.095, 0.117, 0.12)	(0.27, 0.29, 0.31, 0.32)
Glass (kg)	(0.22, 0.22, 0.22, 0.22)	(0.22, 0.22, 0.22, 0.22)	(0, 0, 0, 0)
Filter paper (kg)	(1.95, 1.95, 1.95, 1.95)	(0, 0, 0, 0)	(1.95, 1.95, 1.95, 1.95)
Electricity (kWh)	(312, 321, 325, 330)	(328, 328.5, 328.5, 329)	(320, 322, 323, 327)
Washing water (kg)	(0, 0, 0, 0)	(2190, 3285, 4380, 5475)	(0, 0, 0, 0)

Table 6.6. Results of fuzzy eco-design assessments

	Concept '*x*' (separate heat)	Concept '*y*' (permanent filter)	Concept '*z*' (insulted jug)
Fuzzy impact (mPt)	(12052, 12483, 12664, 12918)	(12548, 12623, 12669, 12739)	(12458, 12546, 12601, 12762)
Optimistic (d_o) (mPt)	12395	12612	12533
Balanced (d_c) (mPt)	12520	12645	12596
Pessimistic (d_p) (mPt)	12695	12679	12637

In the ranking analysis based on COD, only concept '*z*' has the pessimistic impact (i.e., 12637 mPt) smaller than that of the original design (i.e., 12663 mPt), while both concepts '*x*' and '*y*' has higher pessimistic impacts. By the COD analysis, concept '*z*' belongs to case 1, while concepts '*x*' and '*y*' belong to case 2. In sum, all three concepts indicate fair potential to reduce environmental impacts. If the development resources are limited, it is suggested to adopt concept '*z*' as it is the "safest" direction to reduce environmental impacts.

In the ranking analysis based on CMC, three concepts are compared in view of d_o, d_c and d_p separately. It is found that concept '*x*' has the best optimistic and balanced impacts, while it has the worst pessimistic impact. It reflects the original idea that concept '*x*' is relatively innovative compared to other concepts. Thus, it has higher uncertainty about its environmental performance. If the company has adequate resources to take the risk, concept '*x*' can be a possible choice to distinguish itself from other competitors' products.

In sum, the utility of the decision analysis in this study is to describe uncertain environmental impacts of each design concept in view of three indices (balanced, pessimistic and optimistic). These indices are based on the fuzzy estimation of engineering quantities and derived by fuzzy arithmetic. The values of three indices are based on Eco-indicator 99 so that the quantitative differences are meaningful for engineers to assess each concept.

6.4.4 Eco-Design Fuzzy Assessments

It is considered that the utility of quantitative analysis in this research is not simply about comparing different index values. Though the three concepts are proposed by engineers, they do not necessarily know the environmental impacts implied in these concepts. Then, the common request from industry is a decision tool for providing general impressions over some design concepts at hand. The quantitative analysis has two major parts in this research. Firstly, Eco-indicator 99 provides a set of eco-indicators for summing environmental impacts from different sources. Secondly, engineering quantities as specific aspects of design concepts can be highlighted for environmental assessments such as energy consumptions, structure materials and consumable materials.

Besides the ranking analysis (e.g., COD and CMC), the whole framework of quantitative analysis can generate usable information for engineers in environmental assessment. First of all, engineers can find which aspects contribute most to the environmental impacts. For example, by checking Table 6.3, electricity contributes about 95% of the overall impact (i.e., 12154/12663). Thus, it is sensible to focus on the reduction of electricity from environmental improvement. In fact, both concept '*x*' (innovative but risky choice) and concept '*z*' (safe choice) are selected for the improvement over electricity usage. Alternatively, concept '*y*' intended for saving consumable materials is relatively weak in view of reducing environmental impacts.

Also, when a concept is selected, the quantitative analysis provides some benchmarks that further development effort can focus on. For example, if concept '*x*' is adopted, it is noted that engineers should mainly focus on the reduction of electricity. Even more structure materials are required (e.g., polystyrene and steel), the saved electricity can compensate quite easily. This kind of knowledge is not apparent until some quantitative analysis is done.

Originally, LCA is intended for full-scale assessments over various environmental impacts, and it is definitely important for policy makers. While the information from LCA is valuable, the research issue is how to make it accessible even at the conceptual design stage. Eco-indicator 99 has contributed largely for providing easy-to-operate eco-indicators for designers. This study further captures the uncertainty information via fuzzy numbers and arithmetic. This is another contribution of this thesis.

6.5 Summary

While LCA has become a popular tool for environmental design, this thesis proposes a fuzzy assessment method that allows engineers to utilize LCA knowledge (in terms of eco-indicators) for decision making at the conceptual design stage. Particularly, it helps engineers to assess different design concepts for reducing environmental impacts. The technical contributions of this work are twofold. Firstly, three measures (i.e., balanced, pessimistic and optimistic) based on trapezoidal fuzzy numbers (TrFN) are developed to capture various risk aspects in the assessments. Secondly, decision schemes have been developed to compare different design concepts in the ranking process. In the application, a coffee maker is adapted to demonstrate the methodology and examine how the uncertain information can be conveyed from design estimations to environmental assessments.

The obtained results based on the above work have been published in ASME conference[5]. This work is also submitted to ASME Journal[6], adding the comparison of materials with Monte Carlo simulations.

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[5] ASME International Design & Engineering Technical Conferences & Computers and Information in Engineering Conference, Buffalo, USA, 2014.

[6] ASME Journal of Mechanical Design. June, 2015.

Chapter 7 : Conclusions

In this chapter, the presented research in this thesis is summarized. The contributions of this research work are highlighted. In addition, the future development suggested in this research is reported. Finally, the published and the organized works for publication based on our results and contributions are listed at the end of this chapter.

7.1 Summary

The consideration of environmental issues in design activities is unavoidable nowadays. In this thesis, a method of eco-design improvement at the conceptual design stage is developed. In the method, a relational matrices model is developed to capture the information of the existing design. The model is used as a platform to integrate quality function deployment (QFD) and functional analysis (FA) for eco-design. Consequently, relational matrices are developed to support design concept generation and selection. The developed method is integrated using various quality tools such as QFD and Pugh chart to support the streamlining of the design process.

In the developed model, four design information elements are determined based on an existing design. These are requirements (R), metrics (M), functions (F), and components (C). Three relational matrices RM, MC and FC are formulated based on QFD and FA. The notion of constructing the matrices is to capture the relationship strength of design information in a mapping process. The matrix entries are evaluated by quantitative values "1, 3, 9". These measures are used in several studies to quantify the mapping relationships. The systematic mapping in the developed method can support engineers to identify and prioritize eco-design requirements.

After the relational matrices are constructed, these matrices are analyzed for the two design activities, design concept generation and assessment of design concepts. In the generation of new design concepts, *RF* matrix is derived based on the mapping process using matrix multiplications of *RM*, *MC* and *FC* matrices. The existing design functions in the matrix allow the procedure to continue systematically and lead to the evaluation of the design process objectively. Then, a morphological chart is applied to generate new design concepts. Next, two methods, Pugh chart and fuzzy assessment, are selected for the evaluation and selection of the new design concepts. In Pugh chart, engineering metrics are used as measures to evaluate the new concepts.

In fuzzy assessment, this thesis proposed the use of fuzzy numbers to capture the imprecise design information at the conceptual design stage. It has been found, based on the uncertainty of design information, that this case fits with trapezoidal fuzzy numbers (TrFN). In this context, three measures are chosen for ranking fuzzy numbers: balanced, optimistic and pessimistic. Then LCA is applied for the assessment associated with Eco-indicator 99. Subsequently, a decision guide is also proposed to suggest the course of actions with the results of fuzzy assessments. The applicability of this integration is demonstrated through a home appliance (i.e., a coffee maker).

Finally, as this research focuses on the improvement of existing design, three case examples are applied in two different contexts: home appliances (i.e., a coffee maker and hair dryer) and the diaphragm forming process (DFP). These examples have demonstrated the applicability of the method, and the method can provide guidance to designer and manufacturer to assess environmental issues from concept generation to decision making.

7.2 Contributions

The original contributions of this thesis concern the two design activities: (1) design concept generation and (2) assessment of the design concepts. These contributions are reported as follows:

- This work has developed a unique relational matrices model to capture the necessary design information based on an existing quality tool (i.e., QFD) and functional analysis (FA). The developed approach provides improvement of designs at the outset. In the development procedure, mapping analysis is applied to link between eco-design requirements and design functions for prioritizing design functions. Then, a morphological chart is applied systematically to generate new design concepts. The developed relational matrices are demonstrated via two case examples, a coffee maker and a hair dryer.

- In eco-design concept selection. The uncertainty information is captured at the early design stage via fuzzy numbers and arithmetic. After that, three measures (i.e., balanced, pessimistic and optimistic) are associated with a trapezoidal fuzzy number (TrFN) for decision analysis. A decision technique is developed to compare new design concepts in the ranking process. In this work, a coffee maker is used for the demonstration.
- The developed methodology allows the extension of the application in different contexts. In this work, the method is first applied for environmental assessment using two home appliances (i.e., coffee maker and hairdryer). Then, the application of the assessment is extended to investigate the environmental impacts of the diaphragm forming process (DFP).

7.3 Future Research

The possible proposed future directions of this study are highlighted below.

- The quality function deployment (QFD) practice has a solid basis for design planning and the functional analysis (FA) practice for conceptual design. Yet, certain features of these practices have not been incorporated in our current method such as benchmarking and trade off. The proposed method provides a solid framework for the extension to include more features for the eco-design method.
- Besides the consideration of environmental issues in this work, the cost and performance of products will be considered as new measures to compare the newly generated concepts. By

including these two measures in the selection of the new design concepts, companies will have the opportunity to incorporate the economic views in the decision making process as well.

- The fuzzy set approach is not common among the LCA software tools. In future work, we will investigate how to incorporate the fuzzy assessment techniques in the existing LCA software tools so these tools can be tailored for conceptual design purposes. The development of the software can provide engineers with a systematic procedure to automate the procedure of the generated design concepts.
- As the eco-design method is applied in the diaphragm forming process (DFP), the future research could involve employing machining methods to fully apply the methodology in the domain of the manufacturing process. In addition, experimental works are also suggested for future development to experimentally examine the applicability of the method.

List of Publications

Conference Papers:

Alemam, A., and Li, S. (2014). *Trapezoidal fuzzy numbers for eco-design assessments in conceptual design*. ASME international design & engineering technical conferences & computers and information in engineering conference, Buffalo, New York, USA, August 17-20, (**Published**).

Alemam, A., and Li, S. (2013). *Integration of quality function deployment and functional analysis for eco-design improvement*. International conference on mechanical engineering and mechatronic, Toronto, Ontario, Canada, August 8-10, (**Published**).

Alemam, A., and Li, S. (2013). *Fuzzy environmental impact assessment for the early design decisions*. International conference on mechanical engineering and mechatronics, Toronto, Ontario, Canada, August 8-10, (**Published**).

Alemam, A., and Li, S. (2012). *Eco-design methodology for the early design stage: a dependency model for impact assessment and decision making*. PhD research proposal. The 12th Product Life Cycle Management Conference, Montreal, QC, Canada, July 9-11, (**Published**).

Journal Papers:

Alemam, A., and Li, S. (2014). Integration of quality function deployment and functional analysis for eco-design. *International Journal of Mechanical Engineering and Mechatronics*, Avestia Publisher, February, (**Published**).

Alemam, A., and Li, S. (2015). Matrix-based quality tools for concept generation in eco-design. *International Journal of Concurrent Engineering: Research and Applications*, (**Submitted**).

Alemam, A., and Li, S. (2015). Eco-design improvement for the diaphragm forming process. *International Journal of Sustainable Engineering*, (**Submitted**).

Alemam, A., Cheng, X., and Li, S. (2015). Trapezoidal fuzzy numbers for eco-design assessments in conceptual design. *ASME Journal of Mechanical Design*, (**Submitted**).

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