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A green product design framework based on quality function deployment process.

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A Green Product Design Framework Based On Quality Function Deployment Process

By

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ABSTRACT

Environmental problems have aroused people's attention to monitoring environmental impacts and developing new technologies for preventing, or at least relieving the expanding burdens. Therefore, a framework for enhancing the implementation of environmentally conscious design and manufacturing is important to designers and manufacturers.

The framework proposed in this thesis is a green product design tool. It focuses on ensuring better environmental performance by means of selecting environmentally friendly design alternatives. Since the environmental performance of a product relies on varied issues including nature resources consumption, manufacturing and distribution efficiency, and end-of-life management, designers have to face complicated trade-offs during the processes of product design. Our framework contains two parts for dealing with the complicated trade-offs. These two parts are (1) the individual assessment for each life cycle stage, and (2) the overall assessment for entire product life cycle. The individual assessment tool incorporates House of Quality (HOQ) with fuzzy set theory and Analytic Hierarchy Process (AHP), and is used in analyzing the interrelations between environmentally conscious requirements and product design criteria. The overall assessment method is based upon the concept of product life cycle design, which involves a four-step analysis so that the comprehensive environmental effects can be captured at the up-front design stage.

The proposed green product design framework is demonstrated by case studies of the fuel tank analysis and the fastener selection. In the fuel tank analysis, a comparison

of environmental performance is made between plastic fuel tanks and steel fuel tanks. In the case study of fastener selection, seven frequently adopted joining methods are evaluated by using the proposed framework. Based on these two case studies, it strongly suggests that the proposed framework is useful in green product design and analysis.

DEDICATION

To my parents and my wife

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Chapter 1 Introduction

1.1 General Introduction and Problem Statement

Modern day environmental problems have aroused people's attention to monitoring environmental impacts and developing new technologies for preventing, or at least relieving expanding environmental burdens. Some existing environmental problems include global climate changes, ozone depletion, nature resources depletion, and soil degradation.

Several research groups have simulated the global temperature change resulting from radiation effects and predicted that the average temperature will increase 2-5°C by the year 2050. Most important, the by-product from the global temperature change will be an expected rise in sea level. As a result of the temperature increase, the anticipated mean sea level will increase about 20 cm by the year 2030 [34]. The available living area will then be reduced significantly.

Ozone depletion will directly affect biological systems, because ozone can absorb ultraviolet solar radiation. Ultraviolet solar radiation that penetrates the atmosphere may cause reductions in biodiversity, climate change and many related environmental problems. Therefore, ozone layer thickness has become a very important index of environmental quality.

The expanding world population has triggered increasing natural resource consumption and depletion rates. For example, the amount of fossil fuels on the earth has become another environmental problem that has attracted people's attention because human beings rely heavily on fossil fuels as an energy resource. Some estimates have indicated a maximum fossil fuel source life remaining of only forty more years under current consumption rates.

In the past, the cost of environmental damage and the cost of draining our natural resources was sometimes underestimated. Very recent research data has reported a dangerous current situation and the potential disastrous consequences if no urgent actions are taken [34]. For example, few years ago, it was found that chlorofluorocarbon compounds (CFCs) harm the ozone layer and it was decided to phase out this chemical in ten years. However, a later report has shown that the negative effects of this chemical on the atmosphere have been underestimated, and this chemical should be phased out much sooner than ten years. Cases like these have forced many manufacturers to deal with environmental regulation changes on short notice and to consider the product design concept of Design for Environment (DFE).

The increasing awareness of changes in the environment has motivated researchers to focus on the innovation of product design theory and improvement of manufacturing techniques. These changes of the environment have also been deeply explored. For instance, the Ecology and Welfare Subcommittee of the Science Advisory Board of the EPA (Environmental Protection Agency) has provided a priority rank for environmental impacts on global scale concerns in the United States.

Relatively High-Risk Problems include:

- Global climate change;
- Habitat alteration and destruction;

- Species extinction and overall loss of biodiversity; and
- Stratospheric ozone depletion.

Relatively Medium-Risk Problems include:

- Acid deposition;
- Airborne toxics;
- Herbicides/pesticides; and
- Toxics, nutrients, biochemical oxygen demand, and turbidity in surface waters.

Relatively Low-Risk Problems include:

- Acid runoff to surface waters;
- Groundwater pollution;
- Oil spills;
- Radionuclides; and
- Thermal pollution.

The environmental problems have resulted in various global warnings and more stringent production constraints. The existing environmental regulations and the anticipation of more stringent ones to come in the near future have been affecting most modern manufacturing companies. European countries, particularly Germany and the Netherlands, have started taking appropriate measures to address environmental problems by imposing environmental regulations on production facilities [33]. Such regulations pertain to smoke emissions, energy use, and responsibility of product recycling. The German government has proposed legislation that would require automakers and electronics manufacturers to take back and recycle the products at the end of their life cycles. These environmental regulations encourage product manufacturers as well as consumers to conserve natural resources. All of these new constraints have forced manufacturers to modify their manufacturing systems and have stimulated product manufacturers to conduct research on environmentally conscious design and manufacturing (ECDM). In summary, the emergence of a "green" trend of product design and manufacturing has been aroused by several facts:

1. more stringent environmental legislation;
2. customers' awareness of using less environmental harmful products and services;
3. "green" products and services competition from similar product manufacturers or industries;
4. significant savings from green product design including waste reduction, energy preservation and materials recovery.

Many different design issues that will be introduced in section 1.2 have been developed in cooperation with the "green" trend of product design and manufacturing. The ultimate goal of these environmental design issues is pursuing sustainable development, that is, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations World Commission on Environment and Development, 1987). A sustainable effort is a long-term, multifunctional, integrated system approach. Generally, a broad consideration including economic, environmental, social, and cultural issues should be involved in sustainable development which is also the key to creating a healthy community. Activities to develop a sustainable base community are comprised of environmental legislation generation, green land usage, resources conservation, energy efficiency, optimum transportation planning, green building construction and green product design/manufacturing.

This research is focused on the green product design that plays an important role in sustainable development. The importance of improving product design methodology may be perceived in today's tremendous product waste generation. The data has shown that in 1988, U.S. industry generated approximately 700 million tons of hazardous waste and 11 billion tons of non-hazardous waste during raw material extraction, material processing, and product manufacturing[1]. In 1992, Americans generated over 180 million tons of municipal solid waste of which only 13% have been recycled [27]. Consequently, it has been estimated that the number of available landfill sites will be reduced from 18,500 in 1979 to 3,250 by the year 2000 [12]. Focusing on the aspect of manufacturing, green product design has to manage all possible environmental impacts throughout the product life cycle. In other words, a green product design framework may provide a means to eliminate much of the load on the environment and curtail the use of regulated materials.

Green product design should incorporate environmental concerns into the material selection, parts design and into manufacturing process improvement. Broadly speaking, green product design aims at conserving nature resources, minimizing depletion of non-renewable resources and using sustainable practices for managing renewable resources. As a result, applying green concepts into product design will be helpful in maintaining

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[1] See U.S. Congress, Office of Technology Assessment, Managing Industrial Solid Wastes From Manufacturing, Mining, Oil and Gas Production, and Utility Coal Combustion, February 1992.

the balance of the ecosystem structure and environmental equity regarding the distribution of resources and environmental risks among generations and elements of society [44].

One of the major issues in this green product design framework is that it takes into account a design concept known as Design for Environment. In recent years, the concept of Design for Environment has been deeply explored and has generated many design guidelines associated with it. In considering these guidelines of Design for Environment for product design, designers have to face many trade-offs among environmental factors, economic considerations and engineering requirements. Accordingly, a product design system that aids in decision making is very important for employing Design for Environment considerations. The present research develops a new framework by which the environmental criteria and the characteristics of engineering concerns can be considered simultaneously. In other words, the framework provides a systematic means to enhance the process of decision making and associate product design with environmental concerns. The developed framework is discussed in detail in chapter 3.

1.2 Design for Environment Issues

Design for Environment (DFE) is a practice by which environmental considerations are integrated into product development. In addition to the traditional design considerations, DFE considers functional requirements, producibility, assembly, serviceability, recyclability as well as environmental effects. It implies that DFE needs to consider the product's performance and environmental impacts throughout its entire life cycle. On the basis of DFE concerns, product design will consider the product's interaction with its physical environment throughout the product's life-cycle including raw material extraction, energy consumption to fabricate the product, transportation, use, disposal and the associated by-products generated from all processes involved in its life-cycle.

One of the most important parts in DFE deals with the product end-of-life management. There are two types of recycling plans for product end-of-life management: closed-loop and open-loop recycling. A closed-loop product recycling system as shown in Figure 1-1 involves reuse and remanufacturing of the components, or recycling of the materials to make the same product over again. A typical example is to recycle aluminum cans to produce the same or similar type of aluminum cans. The various design issues involved in the closed-loop recycling activity are comprised of Design for Disassembly, Design for Reuse, Design for Remanufacturing and Design for Recycling which are all associated with Design for Environment, and will be concerned as criteria for the green product design framework.

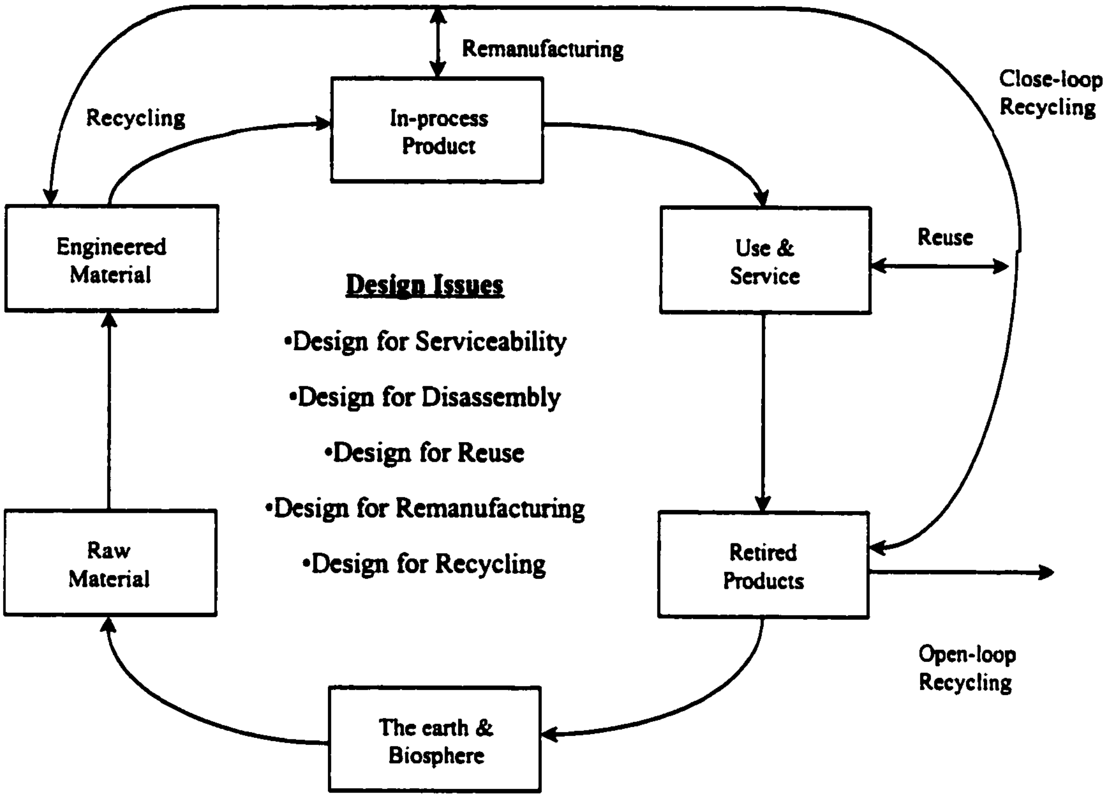

Figure 1-1 The closed-loop product life-cycle system (Adapted from [28])

Another type of recycling plan for product end-of-life management, open-loop recycling, reuses materials to produce a different product. Figure 1-2 shows the profile of open-loop recycling. A typical example of open-loop recycling is that of long fiber office paper which may be recycled to produce short fiber brown paper bags. The application of open-loop recycling will depend on the characteristics of the material. In addition, the process of open-loop recycling usually involves material degradation and waste generation. Thus, it is usually preferable to consider closed-loop recycling first when conducting the product end-of-life management.

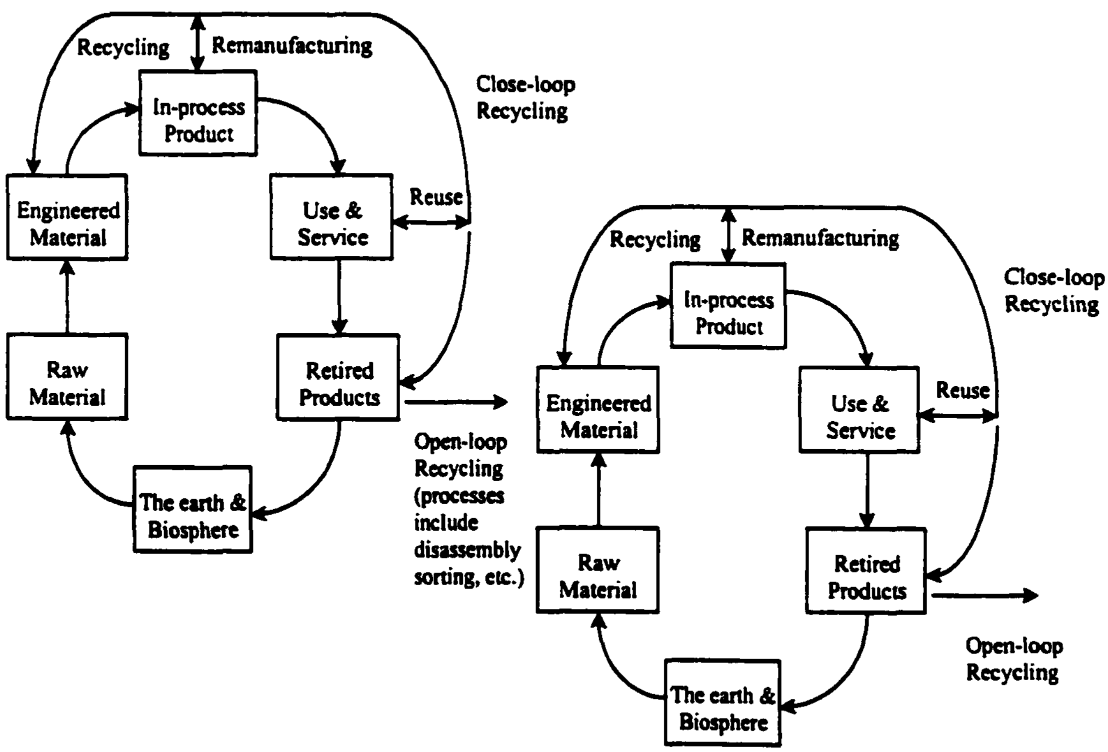

Figure 1-2 The open-loop product life-cycle system

1.3 Framework of the Decision Making Tool

The proposed framework of green product design can be divided into two parts. The first part is the individual analysis, in which fuzzy set theory and Analytic Hierarchy Process (AHP) are integrated into the House of Quality (HOQ). The second part of the framework is the systematic approach, in which a two-phase analysis is developed for illustrating the four stages of the product life cycle. The four product life-cycle stages are: (1) raw material consumption; (2) manufacture and assembly; (3) product distribution and use; and (4) management of end-of-life products. In the first phase of analysis, every product life-cycle stage will be examined individually. The overall assessment is addressed in the second phase of analysis. The HOQ based evaluation tool and systematic product life-cycle approach are addressed in chapter three.

HOQ is a fundamental part of Quality Function Deployment (QFD), which is used to streamline design activities and show a clear understanding of design tasks [11]. One of the important functions of HOQ is to translate customer needs into physical engineering design solutions. In this green product design framework, the element of customer needs is substituted by DFE criteria and the physical engineering design solutions are substituted by alternatives of design features. In other words, the HOQ is mainly utilized to map environmental constraints and concerns to the associated candidates of design features. Moreover, HOQ also provides a powerful evaluation mechanism for measuring the importance of those design features. Therefore, HOQ applied in this framework may enhance the analysis of environmental issues and the prioritization of various design alternatives.

The HOQ approach, on the other hand, has been known to contain some weaknesses [6][35]. They are:

- time consuming process including document preparation and consensus within the design team;
- inconsistency in quantification process;
- use of imprecise artificial variables which contain ambiguity and vagueness of meaning.

Fuzzy set theory is used to deal with the ambiguity and uncertainty in the data involved with relationship definitions in HOQ. In chapter three, how the fuzzy numbers can be used in the implementation of HOQ will be discussed, and the arithmetic operations for fuzzy numbers will be introduced.

There are different DFE requirements under each stage of product life cycle. To fully address the concept of DFE in product design, a systematic approach has to be conducted. By using the systematic approach described in chapter three, the proposed framework can capture the real environmental influence in the full range of the product life cycle. As a result of utilizing the framework, decisions can be made to enhance green product design.

1.4 Objectives of the Research

The anticipated implementation of environmental legislation and standards such as the German in-processing take-back bill and ISO 14000 (Environmental Management System) has motivated industries to do the research relating to DFE issues. Currently, growing insights in the economical opportunities of reuse and recycling encourage designers to integrate environmental activities into product development. The objective of this research is to develop a framework for product design so that the designed products will comply with environmental requirements, and maximize the profits from recycling the used products.

In terms of DFE, use of the proposed green product design framework is mainly expected to achieve profits by: (1) providing a guide to identifying environmentally conscious design requirements; (2) reducing environmental impacts; and (3) increasing the benefits retrieved from end-of-life products. The anticipated activities and profits are itemized below.

1) Provide a guide to identifying environmentally conscious design requirements by:
   - studying the potential restriction in terms of environmental legislation;
   - consulting with experts for expertise; and
   - searching from the available database or library associated with Pollution Prevention (P2), energy consumption and recycle feasibility.
2) Reduce environmental impacts by:
   - reducing the hazardous and nonhazardous residuals from the raw materials extraction and processing, and disassembly processes; and

- reducing the energy consumption of material processing, product manufacturing, and product disassembling.

3) Increase the benefits retrieved from end-of-life products by:
   - configuring the product design for reducing disassembly times;
   - increasing recyclable materials; and
   - reducing landfilled materials.

For implementing DFE considerations in product design processes, a proper decision making tool has to be developed for dealing with the complicated DFE requirements. In addition to incorporating DFE concerns into product design processes, the objective of this research also aims at developing an appropriate decision support system. Although the nature of HOQ provides the function of analyzing interactive criteria, it still has weakness of handling ambiguous information. Therefore, the development of a modified HOQ is another goal of this research. The activities involved in modifying HOQ include:

1) Rearranging HOQ structure: The rearranged HOQ provides a structure where the relationships between alternatives of design features and environmentally conscious requirements may be analyzed.
2) Transforming subjective determination of importance weightings: The Analytic Hierarchy Process will be employed for determining the importance weightings along with DFE requirements and constraints.
3) Substituting artificial expressions (e.g. weak, medium and strong relationship) with fuzzy numbers: the use of fuzzy numbers may solve the vague and imprecise quantification process in HOQ.

4) Developing a systemic approach for green product design evaluation in which the concept of product life-cycle design is incorporated into the overall assessment analysis.

In short, the proposed green product design framework focuses on seeking better environmental performance by means of selecting environmentally friendly design alternatives. The environmental considerations used for guiding the selection include environmental impact reduction throughout the product life cycle, efficiency in the use of nature resources, waste control through production processes, and end-of-life management. As a result, the designed parts or products will meet environmental regulations, standards and ecological requirements.

Chapter 2 Literature Review

2.1 Design for Environment

Along with an increasing awareness of the importance of environmental protection and the trend towards stringent legislation proposed by many developed and developing countries, various environmental technologies are continuously being explored in order to moderate the expansion of environmental impacts and avoid costly environmental penalties. The term, Design for Environment (DFE), is therefore becoming an important objective in the product design process.

In addition to the traditional product design considerations which lead the product design to satisfy functional requirements and specifications, the goal of DFE is to develop more environmentally friendly products without compromising cost, quality, or manufacturing time. DFE also has been known as a systematic consideration of environmental impacts, resource depletion and human health over the whole product life cycle [62]. Therefore, for attempting to achieve the goal of DFE, attention to DFE should be paid throughout all the product design stages which consist of conceptual design, detail design, manufacturing process determination and product end-of-life management. This developed green product design framework provides a systematic approach to incorporate DFE into the product design process and directs the design to corresponding environmental requirements and regulations.

2.1.1 Scope of DFE

The scope of DFE is shown as Figure 2-1. In general, DFE can be categorized into waste prevention and materials management [79][84]. Waste prevention refers to reduction or elimination of wastes generation which is performed during the design or redesign of products and the associated production processes. To implement the behavior of waste prevention, the following guidelines should be considered [30][41][79]:

- Material substitution – replacing toxic materials with less environmentally harmful alternatives, and selecting better manufacturing processes which generate less toxic waste.
- Waste source reduction – reducing waste and practicing material conservation whenever possible in the manufacturing process.
- Energy use reduction – reducing the energy required to produce, transport, store, use or dispose of the product.
- Life extension – prolonging product useful life, increasing product durability and facilitating reparability, so as to reduce the waste stream generated by disposing of the retired product.

The other category associated with DFE is materials management. Under this category, considerations of how to facilitate product recyclability are made. In other words, the application of product retirement is managed within this category. Material management should be arranged early in the product design stage. Accordingly, it is necessary to consider the following management alternatives that lead the product toward a better waste management.

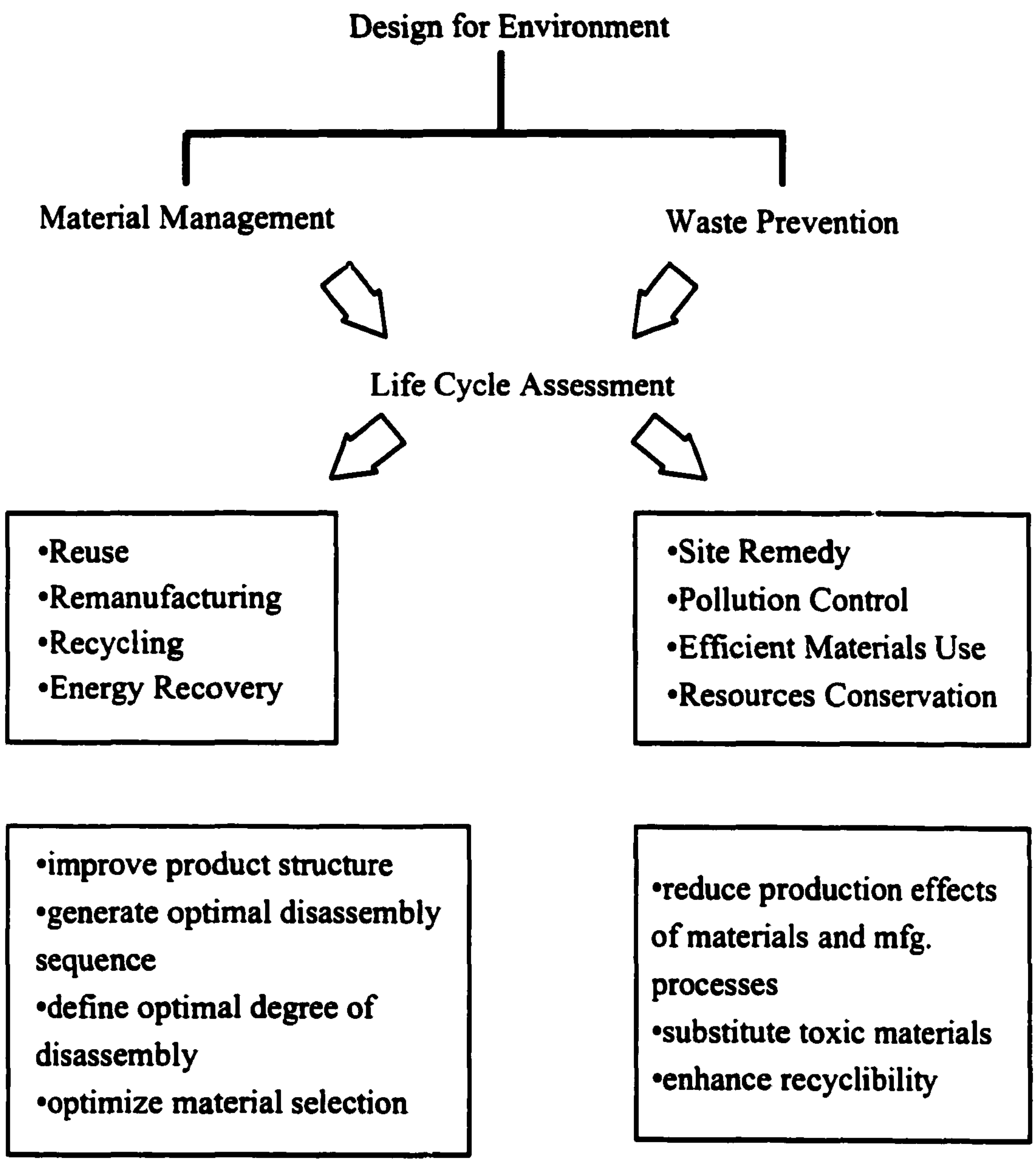

Figure 2-1 Scope of DFE

- Reuse – reuse is the additional use of an item after it is retired from a clearly defined duty. However, repair, cleaning, or refurbishing to maintain integrity may be done in transition from one use to the next [28].
- Remanufacturing – remanufacturing is an industrial process that restores worn products to like-new condition. In a factory, a retired product is completely disassembled. Its reusable parts are then cleaned, refurbished, and put into inventory. Finally a new product is reassembled from both old and new parts, creating a unit equal in performance and expected life to the original or a currently available alternative [28].
- Recycling – recycling is the reformation or reprocessing of a recovered material. Recycling may be defined as "the series of activities, including collection, separation, and processing, by which products or other materials are recovered from or otherwise diverted from the solid waste stream for use in the form of raw materials in the manufacture of new products other than fuel [28].
- Energy recovery – energy recovery is extracting energy from waste materials through incineration or other processes.

In the application of implementing the management alternatives of reuse and remanufacturing, a typical five-step processing stage has been identified which is also the product end-of-life processing stages [14][80]:

1) Disassembly;
2) Cleaning components;
3) Inspecting, testing and sorting components;
4) Upgrading component or component renewal;

5) Reassembly.

With respect to the assessment tool of DFE, Life Cycle Assessment (LCA) is the most frequently used evaluation methodology. According to the Society of Environmental Toxicology and Chemistry (SETAC) [34], the definition of the LCA process is "an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases on the environment, and to evaluate and implement opportunities to effect environmental improvements." The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/re-use/ maintenance; recycling; and final disposal. LCA is, therefore, used as an overall assessment tool which evaluates the potential environmental effects of the design process, while DFE directs the design to minimize environmental impacts. The three phases involved in LCA – Inventory Assessment, Impact Assessment and Improvement Assessment – will be explained in Section 2.3.

2.1.2 Design for Disassembly

In Germany, manufacturer take-back-and-recycling laws have been proposed by the government for automobiles, electronic goods and other durable products. This trend of stringent legislation has forced industries to pay greater attention to product disassembly design. Lindsay Brooke [17] mentioned that automotive designers and manufacturers can help in solving potential environmental problems through three methods:

- Source reduction (reducing the amount of material entering the waste stream)
- Design for Disassembly (DFD)
- Specifying and using recycled materials.

With respect to Design for Disassembly, auto manufacturers have made efforts worldwide. For instance, in Europe, BMW's 1991 Z1 roadster model with plastic body panels was designed for disassembly and labeled as to resin type so they may be collected for recycling [18]. In addition to BMW, Volkswagen has set up disassembly and recycling plants in order to comply with the upcoming recycling regulations. Consequently, they are trying to make an automobile out of 100 percent reusable/recyclable parts by the year 2000. In America, General Motors, Chrysler and Ford, formed the Vehicle Recycling Partnership (VRP) in 1991 to develop ways to recover and reuse as much of the fluff and metal scrap from motor vehicles as possible [63]. Ford has also issued its own worldwide Recycling Guidelines, which suggest fewer and more dismantle-friendly fastener types, 'green' materials and component designs [16].

While the auto industry sees only potential benefits, some electric appliance manufacturers have already profited from launching their DFD/recycling program [21][59][81]. For instance, Xerox has saved $200 million a year through reuse of parts; the focus on green design increased this amount by $50 million.

DFD is a part of DFE and is strongly related to the goal of material management (see Figure 2-1) because DFD is the path toward better product post-life management [9].

It will make disassembly practices easier so that post consumer products may be separated with less effort into parts and materials without contamination. For example, incorporating DFD into product design will eliminate the use of mixing copper and tin in steel. In short, DFD is a very important design concept for post consumer product reuse, remanufacturing and recycling [60], and may lead us to achieve the goal of DFE. The current DFD development may be found in the following perspectives:

- developing DFD guidelines;
- developing cost models for DFD evaluation;
- studying the possibility of using robots to facilitate automated disassembly;
- studying the feasibility of DFD related legislation for enhancing environmental preservation.

The scope of DFD is shown in Figure 2-2 [77]. The ultimate goal of DFD is to extend the life of used parts by means of reuse or remanufacturing, or to provide a new life of the used materials by means of recycling. Considering the definition presented previously, reuse is the most desired scenario of DFD, since the profit retrieved from "reuse" can be maximized. For achieving the success of DFD, much research has been done in this field that can be generally categorized as disassembly-oriented product design, economic analysis of disassembly efforts, and disassembly aided tools.

2.1.2.1 Disassembly-Oriented Product Design

Disassembly-oriented product design aims at formulating design criteria and developing design guidelines to be used by designers during conceptual and detailed design. Jovane, et al. listed considerable advantages arising from disassembly-oriented product design which are [41]:

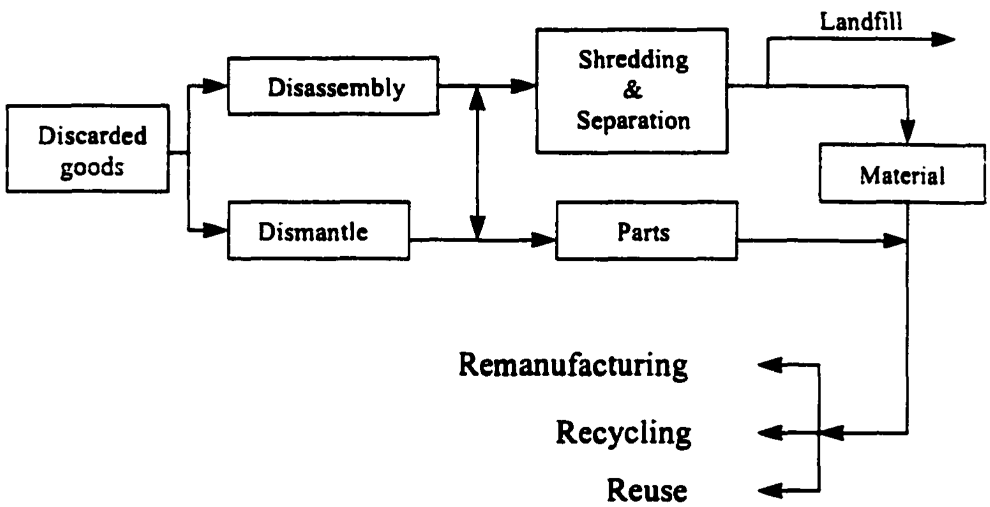

Figure 2-2 Scope of DFD

- less work needed to recover recyclable parts and materials;
- more uniformity and predictability of product configuration;
- simple and fast disconnecting operations;
- easy manual or automated handling of removed parts;
- easy separation and post-treatment of recovered materials and residuals;
- reduction of product variability.

Within the realm of disassembly-oriented product design, one of the most valuable contributions of research is the development of guidelines [13][20][26][41][70]. Those guidelines can be classified as the areas of product structure, material use, and recycling principles and requirements. Table 2-1 demonstrates some of the DFD criteria in each area.

Table 2-1 DFD guidelines

Category	Criteria
Product structure	* Linear and unified disassembly direction * Avoid non-rigid parts * Parts consolidation * Modular structure design * Concentrate hazardous or valuable parts in one area
Material use	* Avoid aging material combination * Avoid corrosive material combination * Protect assembly groups from soiling or corrosion * Limit material variability * Use compatible materials * Avoid metal molded in plastic parts
Recycling principles and requirements	* Include nominal breakpoints * Avoid turning operations for disassembly * Standardize subassemblies and parts for multiple use * Standard and simple joining techniques * Marking of central joining elements for disassembly * Open access and visibility at separation points * Standard gripping spots near center of gravity * Enable simultaneous separation and disassembly * Minimize number of fasteners * Use joining elements that are detachable or easy to destroy * Parts should be easy to pile or store to save room * Design of parts for easy transport * Enclose poisonous substances in sealed units * Avoid secondary finishing (painting, coating, etc.)

The guidelines of DFD are considered to be useful and applicable at the early stage of conceptual design. However, some uncertainties and obstacles exist that will make disassembly activities difficult. For example, the worn-out condition of discarded goods is unpredictable and it may cause joining elements difficult to remove. Particularly, some barriers of DFD result from the efforts made to enhance Design for Assembly. For example:

- some undetachable joining methods are used for enhancing Design for Assembly;
- some unrecyclable materials are used for achieving better performance or more economical manufacturing;
- some structure designs favor assembly and aesthetics, but not disassembly.

Faced with the numerous DFD guidelines, an organized decision support tool becomes very important for designers to deal with the trade-offs among them. However, no such tool exists, and none of the literature referred to above provides a decision aided model to handle the trade offs. Most importantly, the decision tool should be encompassed in design processes so that the designed product may be in accordance with DFD requirements.

2.1.2.2 Economic Analysis

As Simon [70] indicated, the total value of discarded products vary according to whether the high-value items are separated early or late in the dismantling process. In figure 2-3, curve A represents high-value items released early, while curve B does not. Moreover, the value of discarded product will be negative if disposal costs are applied.

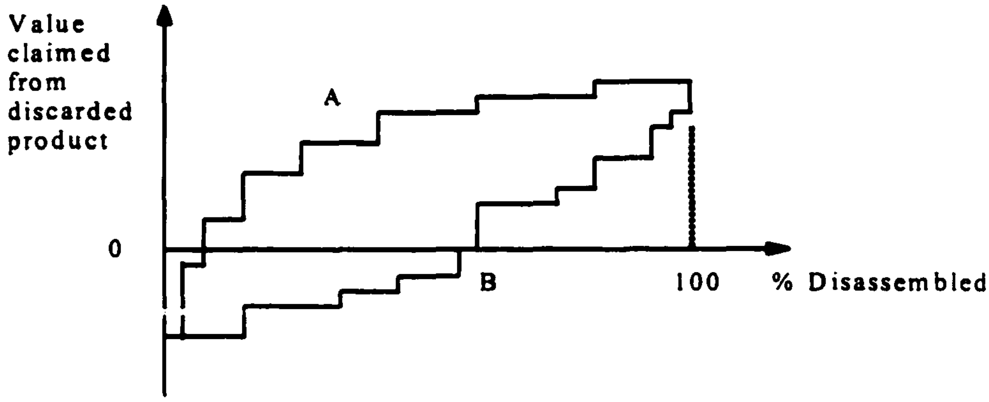

Figure 2-3 Gradient value of material recovery [70]

Johnson and Wang [40] also emphasized that the negative value may result from a number of other circumstances – materials or parts of the product that are toxic require special handling disposal methods; one or more components may have a low material value and existing landfill costs may be high; or negative value may occur in instances where legislation has required recycling and large costs have been incurred to comply with such regulations. In other words, the disassembly sequence is very important in terms of economic considerations. Basically, current researches focusing on disassembly plan are all aiming at separating the high-value items and toxic substances as early as possible in the disassembly process. Based on the economic concerns, the approaches on assessing DFD may be categorized as disassembly path generation [20][40][89] and quantitative evaluation methods [48][51] which all attempt to generate an efficient disassembly scheme.

A typical article discussing the disassembly path generation was presented by Johnson and Wang [40] in which a methodology for disassembly analysis using a cost/benefit tradeoff approach to analyze the potential benefit of material recovery opportunities was addressed. Zussman et al. [89] developed an assessment methodology to support product design for the end-of-life phase. The methodology was combined with probabilistic design method, utility theory and graphical technique where the future recycling conditions (e.g., the price of raw materials, the refinement of process technologies, dumping fees and the development of new regulations) are concerned. Subramani and Dewhurst [74] proposed an algorithm for the generation of optimal sequences for disassembly. In their model, mechanical assembly and disassembly diagrams were used, and the branch and bound search algorithm was applied.

With regard to the quantitative evaluation methods, Chen et al.[20] focused on the analysis of the costs and benefits of recycling. By properly defining a cost function and the benefits of recycling, the disassembly and recycling process can be evaluated. Dewhurst [25] proposed evaluation algorithm index formulas for Design for Service (DFS) and recycling efficiency so that the assessment may be done among DFS, DFD and DFA.

A different disassembly evaluation methodology in which it is not necessary to use disassembly cost as one of the evaluation factors was proposed by Kroll et al. [48]. A worksheet was developed for measures of product "disassemblability", mainly for analyzing small electrical appliances while considering mechanized disassembly.

Even though most of the economic DFD models may have done a good job seeking optimized benefits, there still are some existing barriers. These barriers include:

- the legislation may have been changed when the designed durable product reaches its end-of-life several years later;

- the material recycle chain and technology may not be the same when the product is actually developed, which means the recycle cost may be different;
- the environmental impacts of consumed materials may be underestimated due to limited understanding;
- uncertainties raised by predicting whether consumers will return or recycle the retired products or not.

Therefore, a fundamental requirement for a product design framework will have to involve the capability of dealing with uncertainties of environmental effects.

2.1.2.3 Disassembly Aided Tools

In order to deal with the huge number of tradeoffs associated with environmentally benign product design, a comprehensive computer aided design tool is necessary. Ideally, a computer-aided tool for design for recyclability and disassembly has to involve, at least, a systematic assessment model, hypermedia-based information systems, automatic optimization of the disassembly sequence, and an enriched data base which includes information such as the standard times of disassembly operations and the environmental effects of materials used [72].

These numerous environmentally friendly product development issues reveal that DFD has been noted as a useful tool leading industries toward close-loop product recycling. Two particular industries, the automotive and the electrical appliance industries, have reported some achievements in new product design based on disciplines of DFD. It is obvious that these two industries will act as a guide to other manufacturing industries by exploring innovative design concepts in the future.

2.1.3 Relevant computer tools

Since complicated tasks are involved in DFE such as Design for Disassembly, Design for Reuse, Design for Recycling, etc., computer tools are becoming more and more important to support design practices. Some available computer tools associated with DFE have been summarized in Table 2-2. These computer tools may enhance the analysis in certain product design aspects. Even though these computer tools will be applied in different areas, they are all undoubtedly aimed at supporting environmental improvement projects.

As explained in section 2.1.1, DFE is an integrated approach in which numerous environmental factors have to be incorporated into the traditional product design process. Within the broad boundary of DFE, huge numbers of criteria need to be simultaneously considered and trade-off decisions looked for. Most of the researches related to DFE, however, focused on identifying the importance of DFE or illustrating some associated guidelines. Even though some of these researches worked on developing a methodology to enhance the DFE process or a computer tool to facilitate decision making, they were not able to handle the uncertainties of quantifying the environmental impacts in order to provide a well-structured decision framework. The present undertaking of a green product design framework will try to resolve the shortage of current DFE development and focus on an organized systematic approach and decision support system.

Table 2-2 List of DFE computer tools

Computer Tool	Applied Methodology	Application Area	Author
Design for Environment	Evaluate the environmental impacts by using a value assessment metric. Analyze the disassembly sequence by linking with the Design for Assembly software.	Financial return assessment of disassembly, disposal, reuse or recycling. Environmental impact assessment results from initial product manufacture and disposal, reuse or recycling.	Boothroyd & Dewhurst
Ecodesign expert system	Integrate a computer-aided design for the environment expert system onto a CAD platform.	The ecodesign model aims at encompassing the whole design process, i.e., from concept to detail design.	Poyner & Simon [61]
ReStar	Algorithm based approach on determining the optimal recovery plan based on tradeoffs between recovery costs and the value of secondary materials or parts.	It provides a design analysis tool for evaluating recovery operations, which may be used in product detail design stage.	Navin-Chandra [54]
Disassembly Model Analyzer	Genetic Algorithms is applied for obtaining the profit-optimizing disassembly plan	It may be used for the modeling and analysis of disassembly for reuse and recycling.	Spicer [73]

2.2 Life Cycle Design

Life cycle Design is a design pattern for understanding the interactions between product design requirements, economic systems and their environmental impacts [44]. It covers a broad spectrum which comprises all of the various design-for-X (DFX) issues. The "X" in the term of DFX stands for all activities in a product life cycle, for example, Design for Manufacturing, Design for Assembly, Design for Service and Design for Disassembly are the parts of DFX [1]. Thus, life cycle design may be regarded as a more comprehensive design concept from the traditional design considerations such as DFA, etc. The life cycle design considers all stages of product life cycle comprised of raw material extraction, manufacturing, product use and end-of-life management. Within every product design process consisting of conceptual design, material selection, structure determination and process design, the environmental effects must be taken into account throughout all product life cycle stages. Figure 2-4 shows the stages of product life cycle.

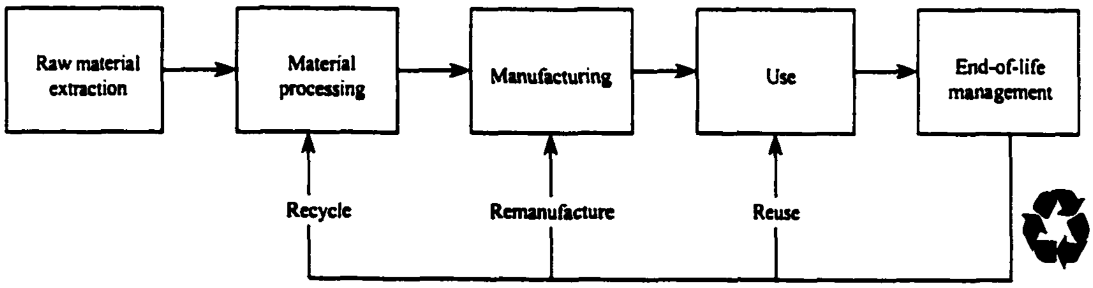

Figure 2-4 Activities of the product life cycle (Adapted from [79])

Alting [4] emphasized that the concept of life cycle design is an evolution of concurrent engineering, and exists in all cycle phases, i.e., needs recognition, development, production, distribution, usage, and recycling. More important, all cycle phases have to be taken into consideration simultaneously from the conceptual product design stage through the detailed design stage. Figure 2-5 shows all elements in the life cycle design concept.

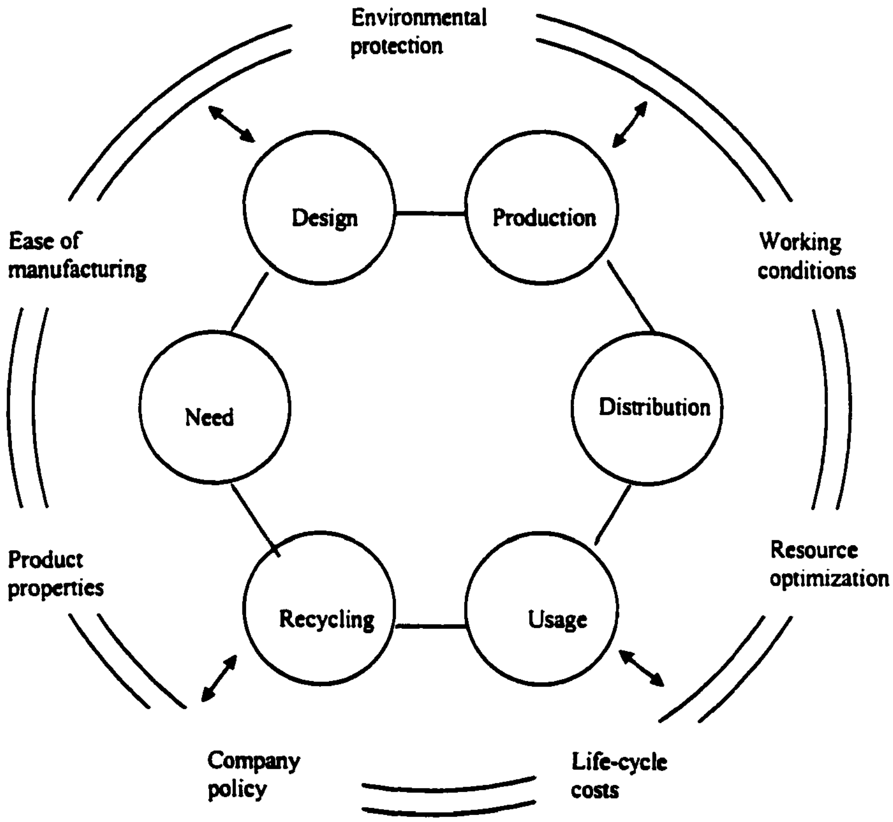

Figure 2-5 Life cycle design concept [4]

As depicted above, life cycle design has similar goals with DFE. Both of them seek to incorporate environmental issues into concurrent design processes. One aspect pointed out by Keoleian and Menerey [44] that may differentiate life cycle design from DFE is that life cycle design also intends to integrate product and process design in a single function to more effectively reduce aggregate environmental impacts associated with product systems. In this proposed green product design framework, a separation of product life cycle stages will be made which is the application of life cycle design. It is expected to provide designers with a clear idea of the boundary of each life cycle stage and the interrelationships between life cycle stages by applying life cycle design.

When conducting life cycle design, considerations must be made to consider the inputs and outputs at each stage of the life cycle. For example, the inputs at the raw material extraction stage would be labor and energy while the output is the actual extraction of raw material from the earth and accompanying waste generation. The critical issue is the final stage – post consumer product disposal and recycling. The inputs of this last stage are the discarded goods from consumers and the outputs to be fed back into previous stages by means of reuse, remanufacture and recycle. This is similar to the idea of sustainable manufacturing, that is, to develop renewable products and strive for no waste residuals between product generations. With respect to the disposal stage, Olson et al. [55] used the term "demanufacture" rather than disassemble since disassembly connotes processes to service the product and which usually do not reduce products to their elementary constituent parts. Demanufacturing relies upon the product design as well as process planning. It involves considerations of facility planning, scheduling, quality assurance and inventory control. For incorporating such broad consideration into the product design stage, a well-organized design framework is very important.

Ishii et al. [38][39] developed a framework that focused on post-manufacturing issues. The model started at the product structure analysis, followed by cost and compatibility analysis. Different from traditional design concepts such as those cost models for Design for Assembly (DFA), life cycle design takes into account company cost, user cost and society cost [4]. The hidden cost (e.g., society cost), including costs for dealing with waste generation, pollution emission and health damage, is sometimes unpredictable. For instance, the emergence of applying CFCs as refrigerant was regarded as a great innovation in energy efficiency. Rapidly, CFCs were used as propellants for blown plastics, foams and aerosols, and as solvents and degreasers. However, the enormous hidden cost of CFCs causing ozone layer depletion was found a few years later. As a result, it is very difficult to accurately create a life cycle design model incorporating comprehensive financial factors. The proposed design framework in this thesis, therefore, focuses on quantifying design guidelines in the evaluation system instead of developing an economic model.

In terms of the life cycle design strategies, a good overview has been provided by Alting and Legarth [5]. As shown in Table 2-3, the overall and subsequent design strategies most often pursued in life cycle design are listed. Those design strategies applied throughout all design processes may be applied for the environmentally conscious selection of materials and components. It ends up with the state-of-the-art in life cycle design. A decision support tool dealing with the trade-off among strategies will be required for implementation of life cycle design.

Table 2-3 Life cycle design strategies [5]

Life cycle phase	
Pre-manufacture	
Strategy	Relevance
Use of recycled materials	Resource depletion, environmental burdens
Use of less energy intensive materials	Environmental burdens
Environmentally conscious component selection	Supplier performance, environmental burdens
Use of renewable materials	Resource depletion
Manufacture	
Use high-throughput processes	Environmental burdens, working burdens
Use material saving processes	Resource depletion, Environmental burdens
Overhead reduction	Environmental burdens
Transportation/distribution	
Improved logistics	Environmental burdens
Low volume/weight	Environmental burdens
Use recycled material for packaging	Resource depletion, environmental burdens
Use	
Low energy consumption	Resource depletion, environmental burdens
Design for maintenance/long life	Resource depletion
Disposal	
Design for disassembly	Resource depletion
Material quality preservation	Resource depletion, environmental burdens

2.3 Life Cycle Assessment

The major obstacle of product Life Cycle Design[2] is that it is difficult to measure the performance of each activity over the product life cycle. Life Cycle Assessment (LCA) has been developed to overcome this difficulty in Life Cycle Design. LCA offers a means for assessing all environmental impacts of a product design from cradle-to-grave [23][28][34].

The objective of using LCA is to evaluate activities and reduce overall environmental impacts. LCA is usually employed by decision makers, whether engineers or government policy-makers, who utilize LCA as a tool to assess the results of the design process; but LCA is not a tool for designing a product.

Figure 2-6 shows that the formal structure of LCA can be divided into inventory analysis, impact analysis and improvement analysis [34][71]. At present, inventory analysis is the most established methodology of LCA while the other two methods still have some difficulties of implementation.

Inventory analysis is used to identify the resource inputs and environmental releases from a production system, and further quantify the corresponding environmental impacts. The inventory process begins with a conceptual goal definition phase to define both the purpose for performing the inventory and the scope of the analysis. An inventory procedure is then employed, and data on the product or system is gathered.

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[2] The term used in this thesis, product life cycle design, is discussing a concept of product design. It is different from the Business and Accounting view point.

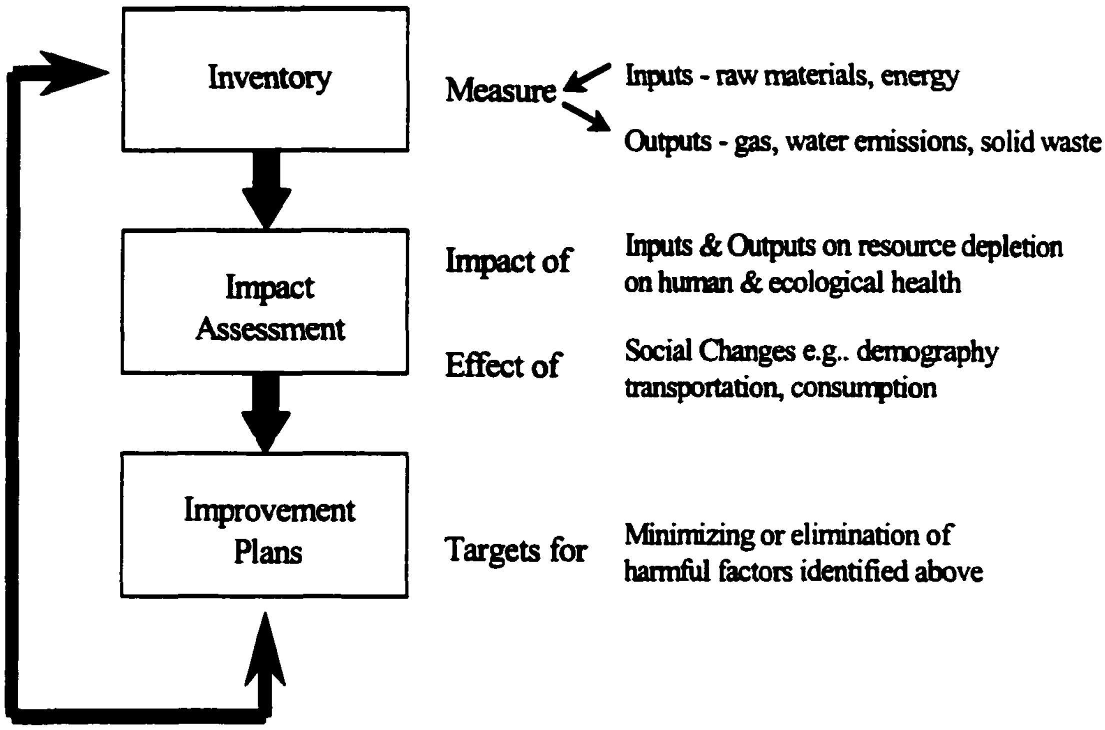

Figure 2-6 Structure of LCA [71]

Impact analysis is the assessment of the consequences associated with wastes being released into the environment. It requires a translation of the inventory analysis factors for an alternative design into measures of environmental impact. This translation relies upon the existence of techniques which can quantify and establish the environmental damage resulting from each of the releases accounted for during the inventory analysis.

The last component of LCA is known as the improvement analysis, in which methods and opportunities for reducing environmental impacts on a specific industrial activity are proposed. It is a systematic evaluation of the needs and opportunities to the environmental burden associated with energy and raw material use and waste emissions throughout the life cycle of a product, process, or activity. The analysis may include both quantitative and qualitative measures of improvement.

By comprehensively accounting for resource and waste input and output, LCAs can keep track of impacts that are typically shifted from one stage of the product's life cycle to another [79]. However, there are several limitations that prevent these methods from been a useful in supporting design decisions; for example,

- the data requirement may not be easily achieved when a broad boundaries of the analysis is drawn;
- the data for a new product or material is not easy obtained;
- the current applications are mainly focused on developing energy and material inventories, and do not address environmental and health impacts or improvement options [82];
- the economic systems in terms of price, consumer behavior are beyond the scope of LCA.

2.4 Quality Function Deployment

Dr. Yoji Akao introduced the concept of quality deployment in the late 1960s. In 1972, the first documentation of quality deployment was published and the powerful tool of quality charts for Quality Function Deployment approach was presented. Two years later, the first application of QFD was reported by the Kobe shipyards of Mitsubishi Heavy Industry. By the late 1970's, the QFD methodology had been adopted by several Japanese companies which reported improvements in communication between departments and new product development being more closely matched with customer requirements. An outstanding product redesign was declared by Toyota through the use of QFD, which has improved the quality of its rust prevention characteristics dramatically since 1977. Over the past decade, QFD has been successfully developed and modified to solve a variety of problems in various industries including mechanical design, electronics, service industries and computer software development.

According to the American Supplier Institute (ASI), Quality Function Deployment (QFD) has been defined as:

> "a system for translating consumer requirements into appropriate company requirements at each stage from research and product development to engineering and manufacturing to marketing/sales and distribution [65]."

Quality Function Deployment, speaking from a functionality view point, is a systematic matrix-analysis tool, mainly for translating the "voice of the customer" into the product or service design by simultaneously considering the relationships between customer opinions and engineering characteristics [64]. Twenty years ago, the QFD process was in its infancy stage and only adopted by a few Japanese industries. Furthermore, at this early stage of application, QFD was only used to direct the companies' planning towards the customers' needs (i.e., "voice of the customer"). Today, QFD has successfully migrated to the U.S. and many European countries and has been broadly applied for improving manufacturing operations, existing product innovations, new product designs, computer hardware, software designs, training and education, company-wide communication, hotel service and marketing planning, etc. A number of big name companies have claimed that using QFD has provided numerous company-wide benefits. In the U.S., these companies include 3M, Ford, General Motors, Chrysler Corporation, Digital Equipment, Hewlett-Packard, AT&T, Motorola Inc., Texas Instruments, NASA Lewis Research Center and Ritz-Carlton [24][37].

2.4.1 QFD Overview

Basically, the QFD is an expansion of the matrix analysis technique called "the House of Quality" (HOQ) [37] in which interfunctional planning and communications are considered [22][64][76]. The QFD assessment tool is constituted by a series of matrices. By means of connecting these matrices, customer needs will be identified and their requirements will be deployed to product, process and production design/planning [2]. Overby [56] described how QFD asks the product design function in organizations to expand its perspective to include more of the life cycle of a product, including a much more integrated relationship between marketing and product and process design and production. The following sections will provide a deeper look of QFD and why this decision support tool is so popular.

2.4.1.1 House of Quality – The Fundamental Element

The earliest use of the term of "House of Quality" appeared in a Japanese quality journal in 1983. The article was written by Nakahito Sato of Toyota Auto Body and later it was translated in English under the title of "Quality Function Expansion and Reliability." [42]

Hauser and Clausing [37] described House of Quality as "a kind of conceptual map that provides the means for interfunctional planning and communications." It is also the fundamental element of QFD and first of a series of matrices in the QFD application process. It has rows in which inputs (e.g., "voice of the customer") are entered and columns from which results are outputted. A description of the systematic format of HOQ [29] is addressed in Appendix A.

2.4.1.2 Series of Matrices

As shown in Figure 2-7, the linkage of these matrices represents the information flow among the product development processes that include product planning, part deployment, process development and production planning. In each individual matrix (i.e., HOQ), the critical criteria may be identified.

The process starts in Phase I, Product Planning, with an analysis of the voice of the customer, and deploys customer demands through the design characteristics of the product. During Phase II, Part Deployment, the information identified in the Product Planning phase will be translated into the critical components' characteristics needed to insure that the customer's requirements are met. In Phase III, Process Deployment, the design team will establish critical products, services and processes parameters needed to meet both customer and design requirements. Finally, in Phase IV, Production Planning, the team chooses the control steps that will ensure the predictability and reliability of the operating processes [24][75]. Used properly, the four-phase system helps the design team deploy diverse customer requirements and prevent conflicts at every major point along the value chain.

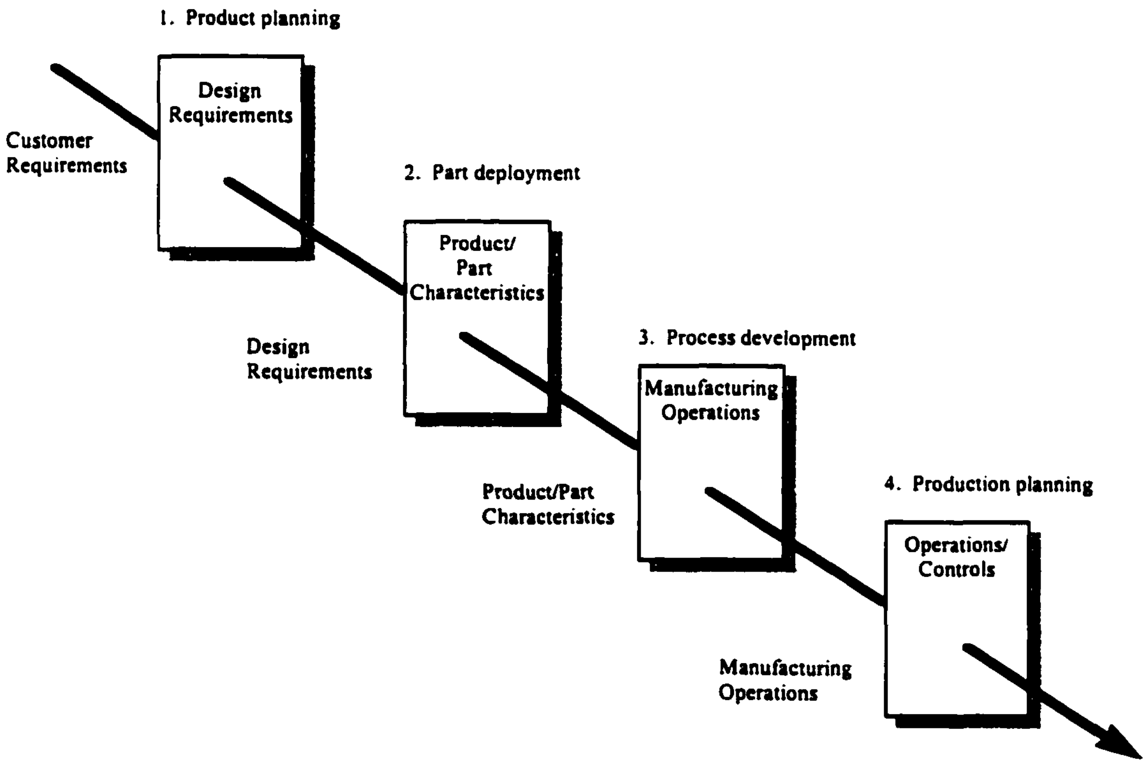

Figure 2-7 The four phases of QFD

2.4.1.3 Benefits of Employing QFD

The major benefit of using QFD is increasing market share. This benefit is realized because QFD plays a major role in reducing production costs and shortening product development times. The expected additional benefits of using QFD have been itemized as follows [35], [65]:

1) Good internal communication: All the participants in the QFD design team will gain a good understanding about the direction they are heading and finally achieve consensus about the decisions being made. Through the QFD process, improvements in internal communication are realized.
2) More efficient product development: Companies use QFD to identify potential long-term problems and to determine which items require new technology. QFD has also been demonstrated to alert companies to conflicts associated with company direction and the infringement of upcoming legislation. By using QFD and tapping the collective knowledge of the organization, the company is able to foresee and avoid costly development problems.
3) Quality and reliability improvement: QFD requires and encourages the use of multidisciplinary teams so that product quality can be improved under cross-functional operations prior to manufacturing.
4) Shorter development cycles: QFD is a system for placing development efforts at the front of a program rather than at the end. With development up-front, the design team can focus on planning and problem prevention.

5) Satisfied customers: QFD forces the organization to keep its focus on the customer. When tradeoffs are necessary, they are made to the customer's advantage instead of the manufacturing department involved. Therefore, QFD ensures that customer's satisfaction is the driving force behind the design decisions being made.
6) Lower costs and greater productivity: QFD not only helps the design team to design and build specification tolerances, but also aids the design team to decide what is important. This allows the team to focus on target values to reduce variation and wastes, and to ultimately lower costs and improve productivity.
7) Comprehensive specification: At the final stage, the design team should end up with a comprehensive specification for their product or service that involves the development, manufacture, and distribution of the product. All of these specifications are required in order to directly trace the design to the customer's needs.

2.4.2 Comparison of QFD and Other Quality Systems

Besides QFD, there are two other well-established quality systems, total quality control (TQC) and total quality management (TQM), which has earned a great attention over the past decade. Figure 2-8 [31][52] provides an overview of these three systems.

It should be noted from Figure 2-8 that QFD has a broader range in the development phase than the other two systems. QFD may be applied as early as getting acquainted with customer requirements and ends with production control, while TQC and TQM have narrow application areas on the product development processes. In short, QFD is not only for quality assurance or quality control, but is considered more of a comprehensive quality system.

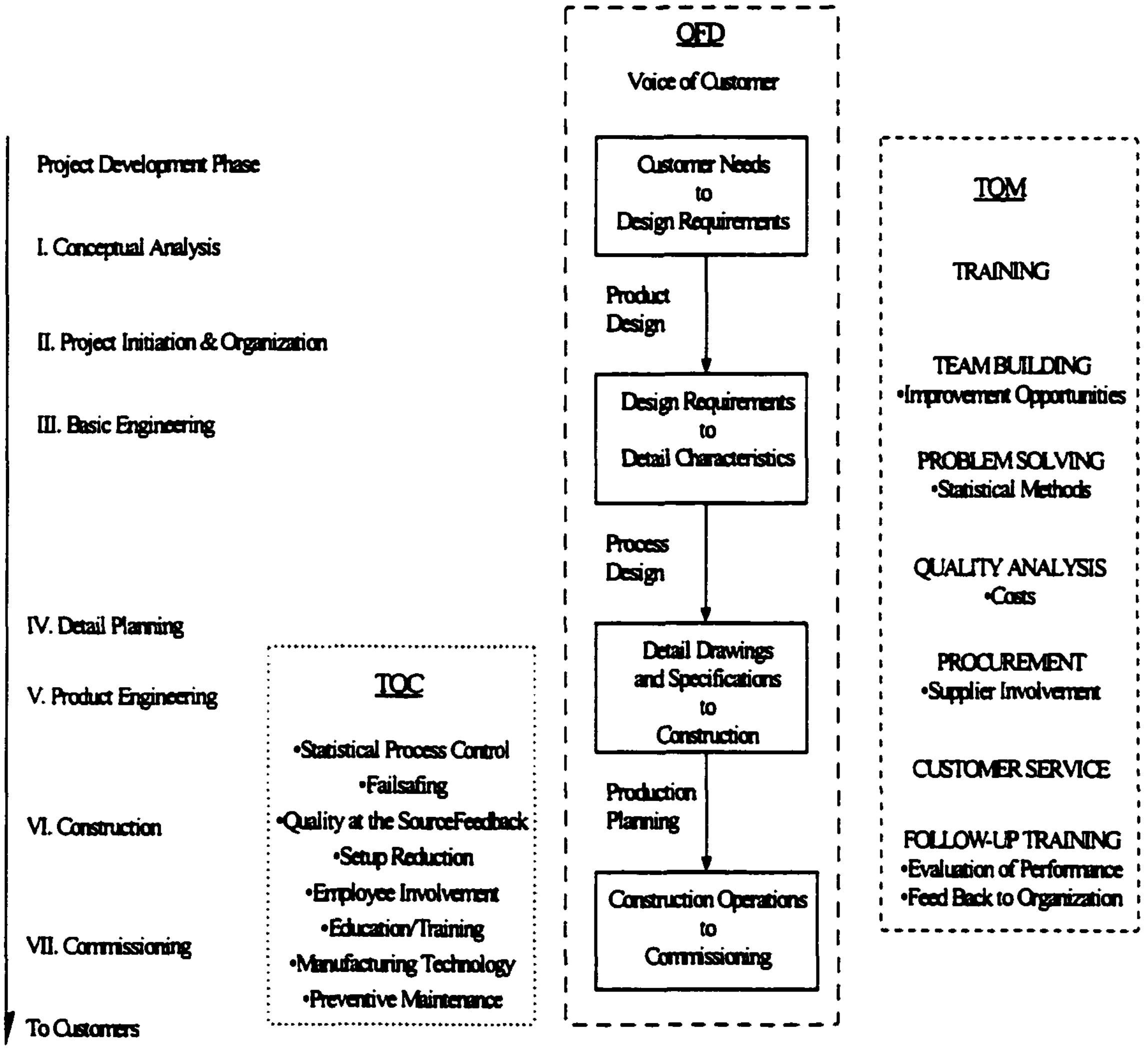

Figure 2-8 Relationship of QFD, TQM and TQC (Adapted from [35][74])

Quality Function Deployment has been extended to apply to environmental decision-making as a support tool [11]. Thus, QFD may have entered into another quality arena in which pollution prevention, waste elimination, material efficiency, long-term liability and recycling efficiency can be handled in a whole. Moreover, this proposed green product design framework will move the QFD to a further place where the principles of design for environment will be incorporated into the whole product life cycle.

TQC, TQM and QFD are the theories/methodologies to implement the practices of current engineering. Since current engineering projects are usually based on a large-scale, an inter-functional design team and professionals in different perspectives may have to work together on the same assignment. Therefore, Design Coordination is another new area derived from the implementation of current engineering. Design Coordination emphasizes the importance of negotiation within the inter-functional design team. The expert systems and knowledge-based tool have been found useful in negotiation [36][85]. Pena-Mora et al. [58] also proposed a framework for collaborative engineering and conflict resolution.

2.4.3 Current Trend of QFD

Quality Function Deployment is regarded as a powerful analysis tool for developing a useful systematic methodology. Even though QFD may be comprised of many advantages as stated previously, a number of users and researchers have identified problems associated with the application of QFD. For example, it has been pointed out that QFD is a very time-consuming process [24] and the rating and computational systems in QFD incorporate vague and imprecise manipulation [75]. In order to overcome these limitations, some QFD literatures have focused on improving the computational system and simplifying the documentation process.

2.4.3.1 Mathematical Model in QFD

A mathematical model in QFD is basically used for quantifying the "voice of the customer", and then prioritizing design resources. Subsequently, the optimal decision may be made in accordance with the priority ranking, and target engineering design levels may be set.

In order to extract qualitative information from the House of Quality, a mathematical programming model has been proposed for determining the optimal combination of multiple quality attributes [50]. The model is based on multiattribute utility theory and optimization theory. The multiattribute utility theory is used to replace the relative importance rating so that the weakness of the QFD computational system may be avoided.

Another attempt at quantifying QFD has been demonstrated using Multiple-criteria Decision Aiding (MCDA) [32]. The MCDA method is an approach to prioritize the engineering design requirements during the QFD process. As a result, this method provides a means of turning the relationship matrix coefficients from an ordinal into a cardinal scale.

A QFD application for determining optimal values of the design process variables was introduced by Belhe and Kusiak [10]. The House of Quality was employed to capture the relationships between various attributes of the design process and the corresponding design process variables. In this methodology, a geometric programming model was utilized to obtain the maximization of the desired function of the process attributes, while the relationships identified in HOQ are used as the constraints.

Wasserman [83] proposed a decision model in which the concept of deployment normalization was introduced. The normalized QFD planning matrix is employed to properly account for dependencies which may exist between design requirements. Followed by the normalized relationships between customer requirements and engineering design requirements, a linear programming model is applied to assist the design team in selecting the mix of design features which results in the highest level of customer satisfaction.

All above literature with regard to QFD illustrates a different mathematical decision model. They are trying to either secure a more reasonable prioritization of engineering design requirements or maximize customer satisfaction in the QFD process. However, none of them can take care of the imprecise information which is usually involved in the expression of measurement of relationships between two attributes. Some works with regard to QFD, on the other hand, focus on solving the semantic expression in the "voice of the customer". The following contains the improvements on QFD in terms of dealing with ambiguity.

Khoo and Ho [46] proposed a fuzzy quality function deployment framework to study the basic requirements of a flexible manufacturing system (FMS). In this fuzzy

QFD framework, the triangular fuzzy number was employed to represent the relative importance and customer ratings. This method may overcome the inherent problem of vagueness and imprecision which results from the use of linguistic weightings such as "strong", "medium", and "weak".

Bahrami [8] introduced a method for performing routine designs by using information content and fuzzy quality function deployment. The linguistic variables associated with fuzzy set theory are used to represent the degrees of difficulty and importance. Consequently, the system and design range can be determined along with manipulating the linguistic variables encompassed in QFD.

Chapter 3 Research Methodology

3.1 Overview

This green product design framework has been organized as two parts. The first part will discuss the individual analysis, while the second part will express the systematic approach. Figure 3-1 shows a simplified flow diagram of the proposed framework.

The individual analysis is the fundamental element of this framework. It is a matrix analysis tool based on the House of Quality, called Modified House of Quality. In this modified HOQ tool, Analytic Hierarchy Process (AHP) and fuzzy sets theory are incorporated into traditional HOQ so that it may be properly applied for Design for Environment analysis.

The modified HOQ has a different matrix arrangement compared to the traditional HOQ. As mentioned in chapter two, the matrix arrangement of traditional HOQ (see Appendix A for detail) is intended particularly for translating the "voice of the customer" into product design processes. In this green product design framework, the modified HOQ is utilized to translate DFE requirements and constraints into product design considerations. The adjusted matrix arrangement of modified HOQ will be discussed in chapter 3.2.

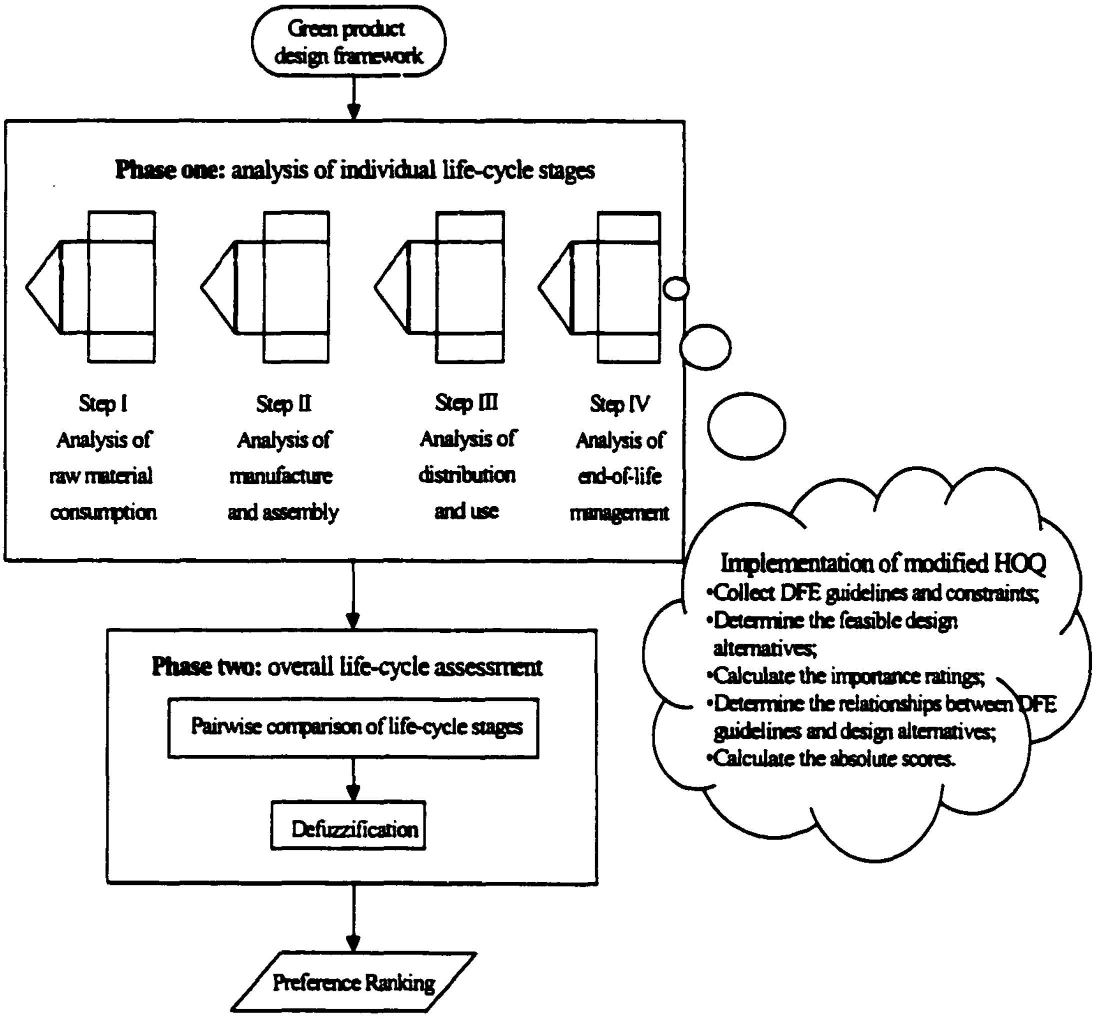

Figure 3-1 Simplified flow diagram of the proposed framework

There are five steps involved in the process of implementing modified HOQ task. These five steps are:

1. collecting the relevant DFE guidelines and constraints;
2. consulting with the design team for the list of potentially feasible design alternatives;

3. calculating the importance ratings in accordance with the results of pairwise comparison among DFE guidelines;
4. determining the relationships between DFE guidelines and alternatives of design features in terms of fuzzy number representation;
5. calculating the total importance score for each alternative of the design features.

The step-by-step explanation of the modified HOQ process is addressed in chapter 3.2.

The second part of the framework is the systematic approach, in which the principle of life-cycle design will be incorporated into the proposed green product design framework. The purpose of using this systematic approach on the basis of product life cycle is to capture the real environmental influence associated with adopting a particular design feature. In order to analyze the environmental impact properly, the systematic approach has been mapped as a two-phase analysis. The two-phase analysis process can be outlined as follows.

1. Phase one: analysis of individual life-cycle stages which includes:
    I. raw material extraction and processing;
    II. manufacture and assembly;
    III. product distribution and use; and
    IV. management of end-of-life products.
2. Phase two: overall life-cycle assessment.

As indicated above, a four-stage analysis of the product life cycle is conducted in phase one. The modified HOQ will be used in each life-cycle stage analysis. In other words, there are four modified HOQ matrices that represent four life-cycle stages respectively to fulfill the life-cycle assessment.

3.2 Modified House of Quality

HOQ is a powerful mechanism that is usually used to transfer customer requirements into product or service design. However, the weakness of HOQ, pointed out in chapter one, includes a tedious implementation process and use of imprecise artificial expressions. In order to employ HOQ as an environmental evaluation tool as well as improve its implementation process, the configuration of HOQ has to be rearranged so that it can evaluate the various design alternatives in accordance with environmental design guidelines and regulations. The rearranged HOQ tool is called Modified House of Quality and that is shown in Figure 3-2.

With regard to the manipulation of imprecise artificial expressions in the traditional HOQ, the fuzzy sets theory has been proposed to be used in modified HOQ for resolving the existing problem. In modified HOQ, a specific fuzzy number will be assigned to represent the strength of relationships between environmental requirements and design alternatives. As a result, the quantitative meaning contained in the relationships may be captured without vagueness.

In short, the modified HOQ aims at enhancing the analysis of green product design and improving the existing shortcomings in the traditional HOQ.

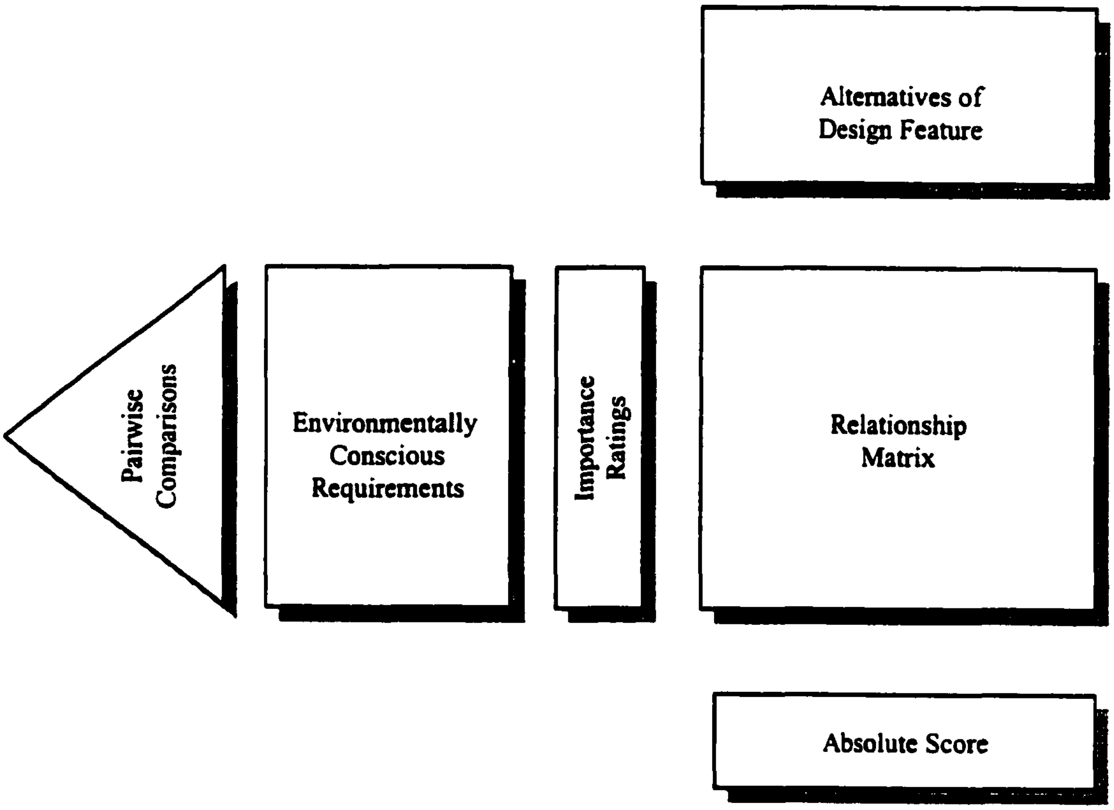

Figure 3-2 Modified House of Quality

3.2.1 Configuration of Modified HOQ

In order to incorporate the HOQ methodology into the application of green product design, a revision to the HOQ is required. This section will explain the modified HOQ, especially the change of configuration.

The major change of configuration is to shift the correlation matrix from the top to the left-hand side. This modification of the configuration may allow the design team to measure the importance among the environmentally conscious requirements. Subsequently, the numerical importance ratings with respect to each environmentally conscious requirement may be calculated on the basis of the relationships identified in the correlation matrix.

The purpose of applying modified HOQ is to evaluate a set of feasible design alternatives and choose the most appropriate one. In order to achieve this goal, the design alternatives have been arranged to display in the topmost matrix so that the total absolute scores may be collected in the bottom matrix. Subsequently, the decision of selecting a preferable design alternative can be obtained on the basis of these absolute scores. Since the correlation matrix has been relocated, some of the matrices in the modified HOQ have different functions from the HOQ's. The comparison between conventional HOQ and modified HOQ is provided in Table 3-1.

Table 3-1 Comparison between HOQ and modified HOQ

Rooms	HOQ	Modified HOQ
Whats	"Voice of the customer"	Environmentally conscious requirements
Hows	Engineering design requirements	Alternatives of design features
Correlation	Measurements of the interaction between the technical requirements	Pairwise comparison of environmental requirements with respect to the corresponding goal
Importance Ratings	Assigned by the design team	Calculated by using AHP in accordance with the results from correlation matrix
Relationship Matrix	Use of linguistic terms to describe the strength of relationship, such as strong, medium and weak	Use of fuzzy numbers to represent the strength of relationship
Absolute Scores	Computed as the sum of product of importance ratings and strength of relationship	Computed on the basis of fuzzy arithmetic operations and interpreted by means of defuzzification

3.2.2 Environmentally Conscious Requirements

Defining environmental requirements may be one of the most critical factors in the whole design process. A well-established set of requirements may enable the design to proceed more efficiently, since design alternatives will be evaluated based on how well they meet requirements. Generally, in terms of engineering considerations, design requirements contain design functions and design constraints. In this study, the focus of design requirements is on environmental aspects, and the specific term, "environmentally conscious requirements", will be used in later sections.

Environmentally conscious requirements represent the environmental regulations and the DFE guidelines identified in the initial product design stage. Since environmentally conscious requirements are product and process dependent, different industries will face a variety of environmental regulations and may want to consider various recycling strategies. Generally, the information in this matrix contains considerations of energy efficiency, material usage, pollution prevention, economic factors, design for disassembly, recyclability, and alternatives of end-of-life product utilization.

It is difficult to collect comprehensive data in this matrix because regulations are rapidly changing and recycling technology is continually improving. In other words, the design team sometimes has to forecast the future development of changing legislation and industrial requirements. Consequently, it will increase the degree of uncertainty and it will be more difficult for the design team to reach a consensus on the value of the importance ratings. There are two methods proposed to overcome this problem. One is developing a matrix-base worksheet to generate environmentally conscious requirements associated with the current product or process. The other one is applying Analytic Hierarchy Process (AHP) to obtain rational importance ratings that will be explained in chapter 3.2.4.

The matrix-base worksheets have been divided into four stages in accordance with the product life-cycle stages, including raw material extraction, manufacture and assembly, product distribution and use, and management of end-of-life products (see Figure 3-3). The four-stage arrangement will comply with the systematic approach in the proposed green product design framework, as well as facilitate the generation of comprehensive design criteria.

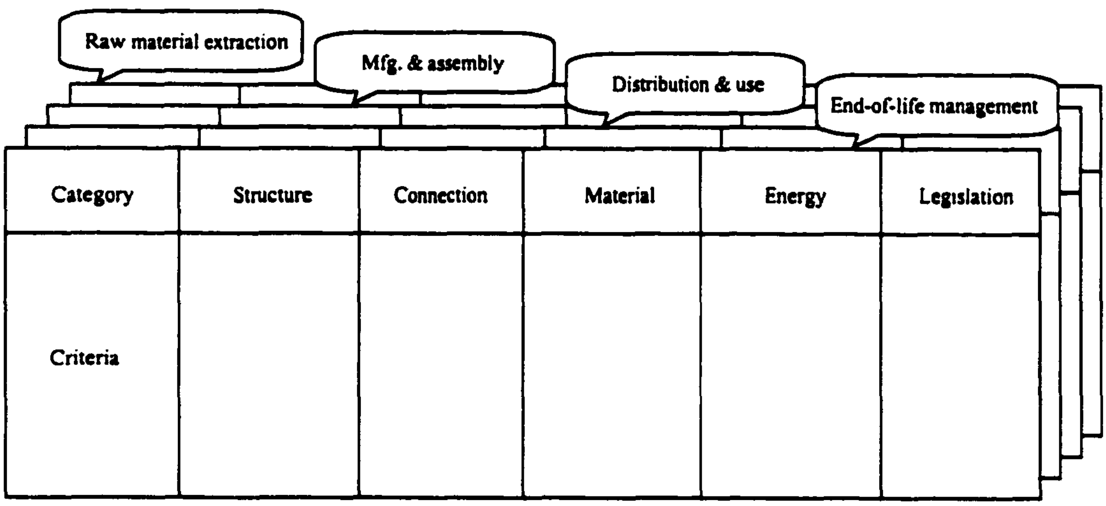

Figure 3-3 Worksheets for environmentally conscious requirements

The worksheet for each life-cycle stage contains columns that represent considerations associated with environmentally conscious requirements. For the purposes of facilitating generation of environmentally conscious requirements and providing a rational weight for each requirement, the categorized considerations are further broken down into criteria. Figure 3-3 shows the configuration of the worksheets. The surface layer in Figure 3-3 represents the end-of-life management stage, while the other three hidden layers are raw material extraction, manufacture and assembly, and distribution and use, respectively.

In terms of DFE guidelines and associated environmental protection laws, there are five categories that can be identified. These categories are (1) product/component structure; (2) connection; (3) material; (4) energy consumption; and (5) legislation. These five categories are all or partially related to each of the product life-cycle stages. Table 3-2 indicates the relationships between the product life-cycle stages and these five categories. The marked intersections indicate that the category is related to the corresponding life-cycle stage.

In order to discover all the environmentally conscious requirements, the design team should look into the potential environmental impacts resulting from adopting a certain design alternative. The environmental impacts should be looked at with respect to depletion of nature resources, violation of environmental regulations, damage to ecological health and risk to human health. In other words, the generalized environmentally conscious requirements attempt to minimize the use of nature resources, comply with environmental laws, minimize the negative impacts outside of the production site, and eliminate harmful emissions to work/consumer exposure environment.

Table 3-2 Categories of product life-cycle stages

Life-cycle stage / Categories	Raw Material Extraction	Manufacture & Assembly	Use & Distribution	End-of-life Management
product structure		√	√	√
connection selection		√	√	√
material utilization	√	√	√	√
energy use	√	√	√	√
legislation	√	√	√	√

3.2.3 Design Alternatives

Design alternatives are the methods that attempt to fulfill customer needs as well as design requirements/constraints. When the design team proceeds through the conceptual design stage, ideas will be generated in correspondence with customer requirements. The ideas are usually obtained from expertise, brainstorming, and/or experience. Since the generated ideas are not required for a preliminary evaluation, it may result in producing multiple design alternatives. Before moving on to further stages of product design, the created design alternatives have to be initially evaluated to screen out unfeasible ones. The proposed framework provides a means to sift out unfeasible alternatives by prioritizing the nominees of design features, for example, by regarding the design alternatives as objects to be analyzed. The generated design alternatives will be placed in the top matrix of the modified HOQ for succeeding analysis processes.

A typical example of design alternatives is the varied fastening mechanisms. A proper choice of fasteners may ensure the successful functioning and the feasible, low-cost manufacture of any product. Figure 3-4 is a classification of joining options available to designers. While the design team performs the fastener selection task, the alternatives may be picked from the classification tree without any detailed assessment. Subsequently, these alternatives will be addressed in the design alternative matrix as the feasible objects that will undergo further analysis.

3.2.4 Importance Ratings

In this implementation step of the modified HOQ, an importance rating of each environmentally conscious requirement will be determined. As mentioned previously, imprecise and subjective weights will be assigned in the traditional HOQ application. Therefore, the Analytic Hierarchy Process is proposed as a method for obtaining rational weights in modified HOQ as an improvement over traditional HOQ.

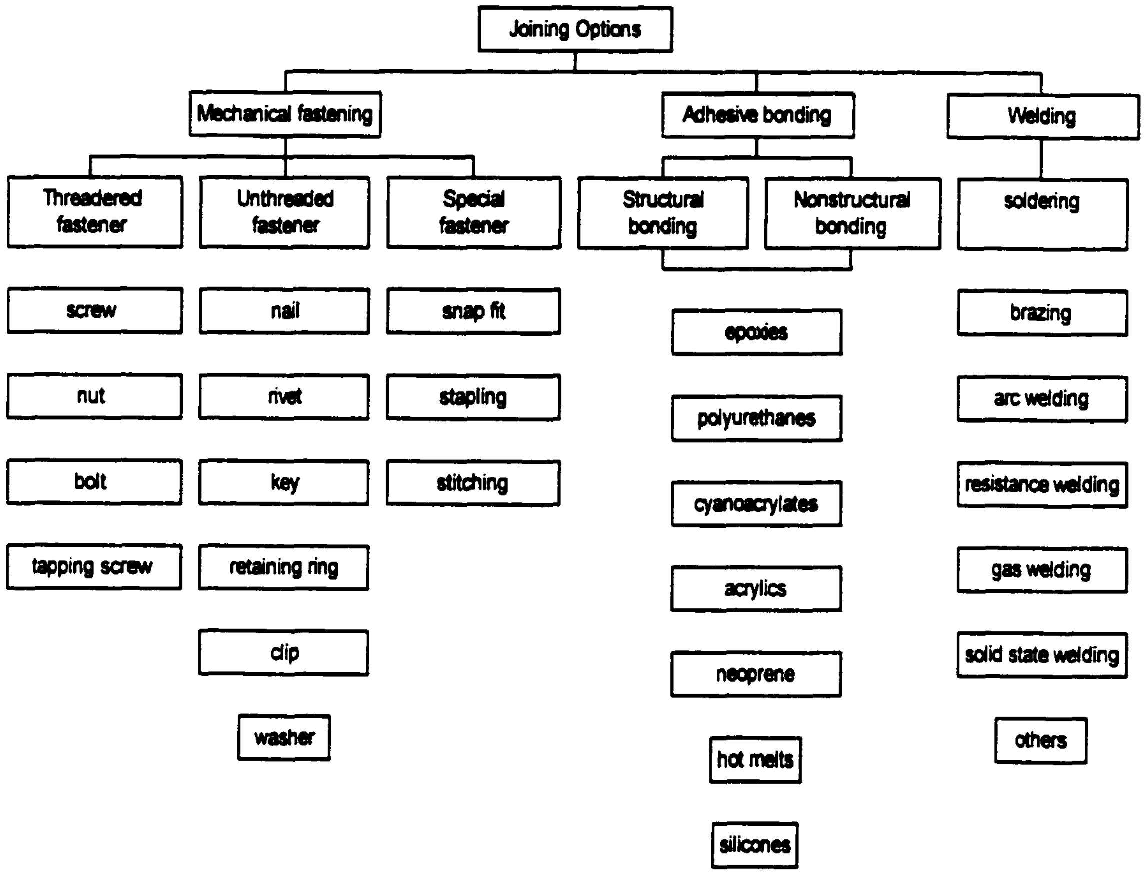

Figure 3-4 classification of joining options

While assigning importance ratings for the generated environmentally conscious requirements, the design team will face other challenges including seeking consensus, making tradeoffs and synthesizing judgement. Nevertheless, the analytic hierarchy process provides a flexible model that allows individuals or groups to organize ideas and derive the prioritized solution. In short, the expected advantages gained from utilizing AHP in modified HOQ include:

- generating comprehensive environmental requirements in a hierarchic structure;
- incorporating judgments and personal values in a logical way;
- enabling the establishment of priorities among environmental requirements by means of pairwise comparison;
- providing a method for tracking the logical consistency of judgments used in determining priorities.

In the following sections, the basic steps of integrating AHP into modified HOQ will be explored. Figure 3-5 shows the sequential acts involved in the process of determining importance ratings. The whole process will start with selecting relevant environmentally conscious requirements from the knowledge base. The pairwise comparison between components in each level of the hierarchic structure will be conducted next. Before moving forward to the overall synthesis step, a consistency check will be practiced in order to ensure that a proper pairwise comparison has been derived. Finally, the outputs will be the computed priorities that also represent the required importance ratings.

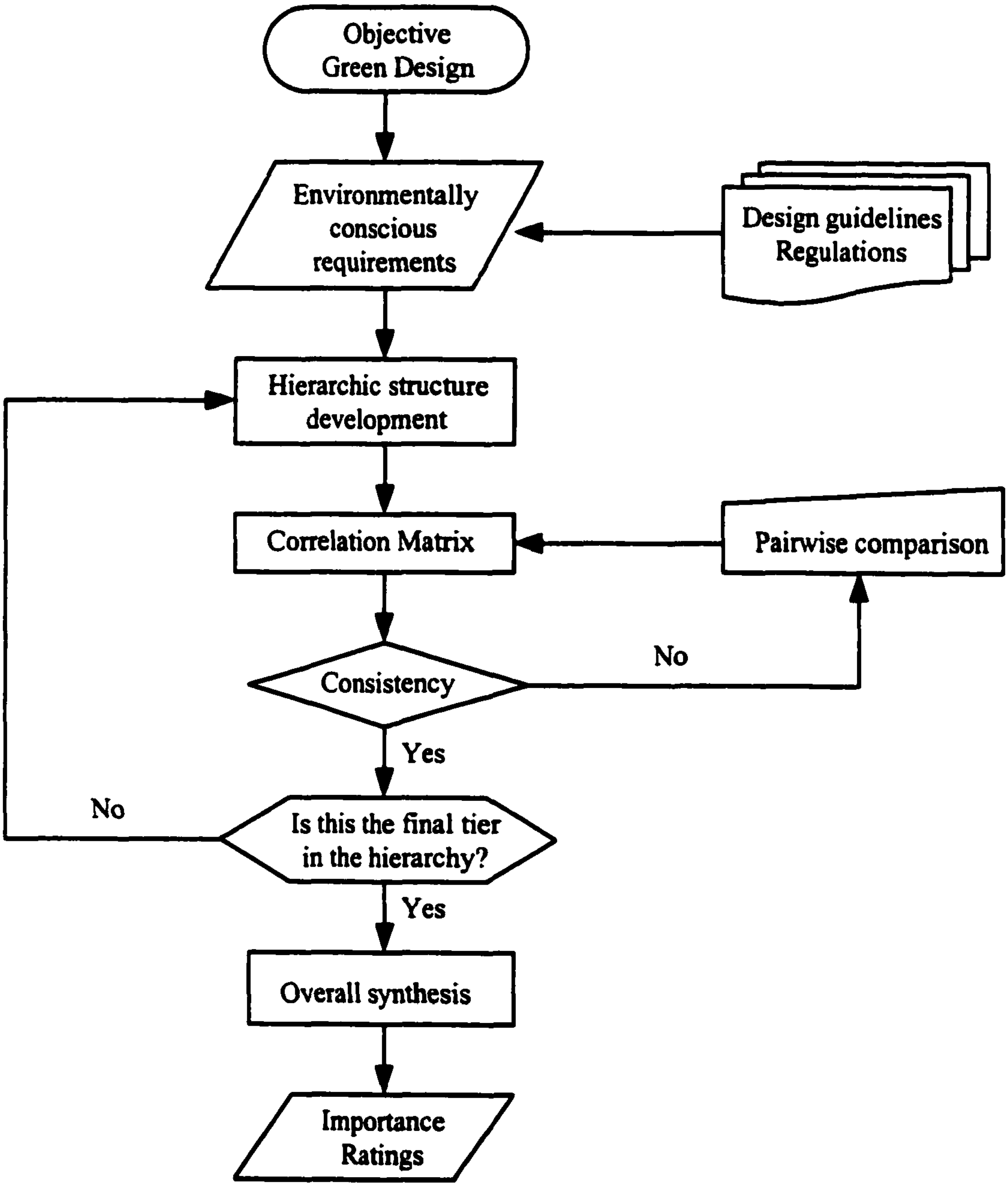

Figure 3-5 The flowchart for determining importance ratings

3.2.4.1 Hierarchic Structure

Structuring a hierarchy of environmentally conscious requirements may provide designers a clear view of design circumstances and a way to penetrate the problems. Basically, the structure is formulated by grouping environmentally conscious requirements into categories. This is the initial step of the Analytic Hierarchy Process. A well-organized hierarchic structure will enhance the succeeding prioritization operations. In essence, partitioning environmentally conscious requirements into more levels will provide a better description of the system. On the other hand, increased structure levels will result in a more complex computation for obtaining the priorities. These two factors are the major concerns while building the hierarchic structure. A rule of thumb of deciding how many levels is appropriate for a system was proposed by Saaty [67]:

By making paired comparisons of the elements in a level in terms of the elements of the next higher level, it is possible to decide on an appropriate choice of that upper level. Moreover, when the elements of a level cannot be compared except in terms of finer criteria than identified so far, a new level must be created for this purpose.

A two-level hierarchy is suggested to be used in this framework. These two hierarchic levels are category and criteria, respectively. This arrangement is also in correspondence with the worksheets developed for producing environmentally conscious requirements (see Figure 3-3).

An example of the hierarchy is illustrated in Figure 3-6, which expresses general design guidelines and relevant environmental legislation of the product end-of-life management stage. The initial step in constructing the hierarchy is setting the analysis goal. In this proposed framework, the goal is always green manufacturing. Under the established goal, the hierarchy of green product design may be broken down into categories that have structure, connection, material, energy and legislation. Once the categories have been identified, they may be further divided into criteria. The criteria encompass design guidelines and strategies for achieving the goal with respect to each category.

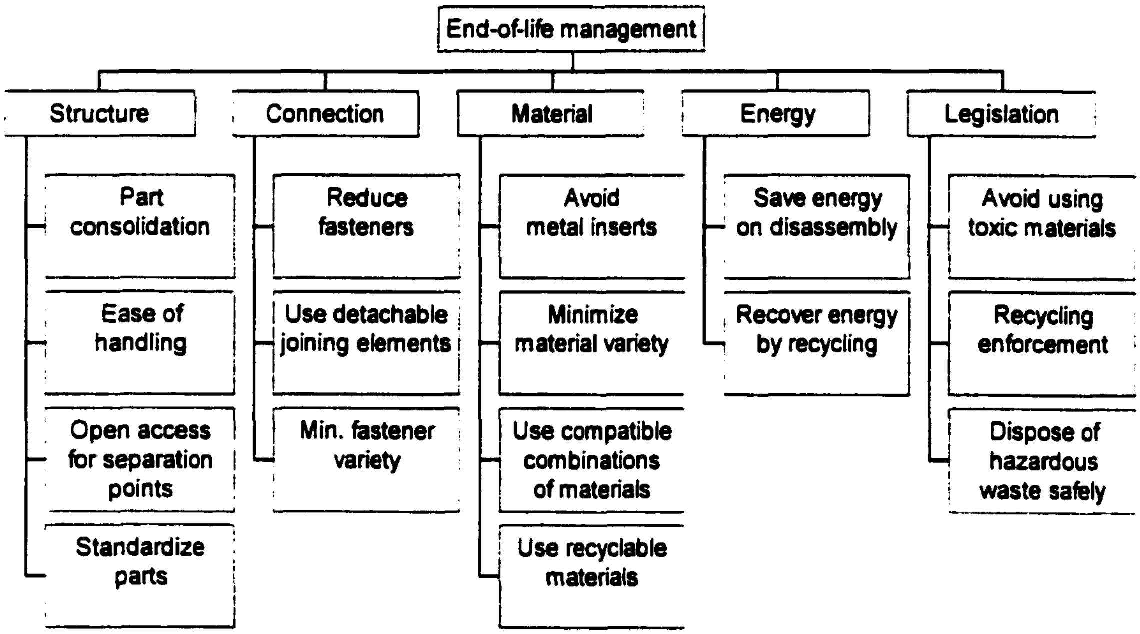

Figure 3-6 Environmentally conscious requirements for end-of-life stage

3.2.4.2 Pairwise Comparison Matrices

In applying the AHP, components of the hierarchy of environmentally conscious requirements are compared in pairs with respect to their relative impact ("weight" or "intensity") on a property or goal that they share in common. The results of pairwise comparison will be recorded in the correlation matrices in the modified HOQ template.

Compared to directly assigning relative weights to each component, pairwise comparison has advantages that give the analyzer a basis on which to reveal his or her preference by comparing two elements. The advantage of pairwise comparison can overcome the shortcomings of direct assignment of weights that is easy to misjudge for the analyzer and may result in inaccuracies.

When comparing a set of components of environmentally conscious requirements with each other, a square matrix may be produced that is in the form of:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{bmatrix}$$

Based on the hierarchy of environmentally conscious requirements (see section 3.2.4.2), a matrix may be formed to compare the relative importance of categories in the first level with respect to the overall objective. Figure 3-7 shows the pairwise comparison matrix for the first level of the hierarchy with respect to the end-of-life management stage. The pairwise comparison matrix is constructed by providing the objective of comparison above and listing the elements to be compared in the heading row and the first column. Similar matrices will be constructed for pairwise comparisons of each criterion in the second level with respect to the categories of the first level. In other words, five more pairwise comparison matrices have to be constructed before obtaining the importance ratings along with environmentally conscious requirements.

The goals for these five matrices are structure, connection, material, energy and legislation, which are the categories in the first analysis level.

Goal: End-of-life management	Structure	Connection	Material	Energy	Legislation
Structure	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
Connection	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}
Material	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}
Energy	a_{41}	a_{42}	a_{43}	a_{44}	a_{45}
Legislation	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}

Figure 3-7 Pairwise comparison matrix for the first level

In Figure 3-7, the variables a_{ij} (i and j refer to the rows and columns) are the relative importance of the components being compared with respect to the goal identified at the top. In order to present the relative importance, a scale of measurement is used that was introduced by Saaty [66][67][68]. Table 3-3 summarizes the scale used in this green product design framework.

There are two important properties of the pairwise comparison matrix. One is the reciprocal property [66], that is:

$$a_{ji} = \frac{1}{a_{ij}}$$

where the subscripts i and j refer to the row and column, respectively, where any entry is located.

Table 3-3 Scale of relative importance (Adapted from [68])

Intensity of relative importance	Description of pairwise comparison
1	Both activities provide equal overall importance to the objective.
3	Moderate importance of one over another with respect to the objective.
5	Strong importance of one over another with respect to the objective.
7	Very Strong importance of one over another with respect to the objective.
9	Extreme importance of one over another with respect to the objective.
2, 4, 6, 8	A compromise is needed between two adjacent importance values.
Reciprocals	If activity i has one of the preceding numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

When comparing activity X with Y, a numerical value from the Table 3-3 will be estimated for the importance ratio. The reciprocal value is then used for the comparison of activity Y with X. The other property is that the diagonal of the matrix is unity, since any component which compares with itself will always give an equal importance. Based on these two properties, pairwise comparison matrices will have the form of numerical judgements as:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{31} & 1/a_{32} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1/a_{n1} & 1/a_{n2} & 1/a_{n3} & \cdots & 1 \end{bmatrix}$$

As long as the two properties hold, pairwise comparison matrices can be further simplified into triangular shaped matrices. The triangular shaped matrices have n(n-1)/2 variables reduced from n^2 variables and will comply with the modified HOQ configuration format. For instance, the first level of the established environmentally conscious requirements worksheet can be organized as Figure 3-8.

<= Structure	<= Connection	<= Material	<= Energy	<= Legislation	
1	a_{12}	a_{13}	a_{14}	a_{15}	Structure
	1	a_{23}	a_{24}	a_{25}	Connection
		1	a_{34}	a_{35}	Material
			1	a_{45}	Energy
				1	Legislation

Figure 3-8 Simplified pairwise comparison matrix for categories

3.2.4.3 Consistency Check

In AHP methodology, the consistency check is one of the most important issues. An analyzer reporting that activity A_1 is twice as important as activity A_2 and that A_2 is three times as important as activity A_3 is providing consistent judgment if the analyzer reports that A_1 is six times as important as A_3. If the analyzer reports any other value for the comparison of A_1 with A_3, the judgment is considered to be inconsistent.

Each pairwise comparison represents an estimate of the ratio of the priorities or weights of the compared activities. Saaty introduced the eigenvector method (see

Appendix B) to calculate the overall weights in each pairwise comparison matrix for each level of the hierarchy. In order to measure the level of inconsistency, the consistency index (C.I.) and inconsistency ratio (I.R.) are utilized. The consistency index may be computed by using the formula [66][67][68] as:

$$C.I. = \frac{\lambda_{max} - n}{n - 1}$$

The formula for calculating the inconsistency ratio is as [66][67][68]:

$$I.R. = \frac{C.I.}{R.I.} \times 100\%$$

where λ_{max} is the largest eigenvalue of the pairwise comparison;

n is the number of elements being compared;

$R.I.$ is the random consistency index [3].

Saaty proposed a rule of thumb that the inconsistency ratio should be less or equal to 10 percent for acceptable results. Otherwise, it is recommended that a certain revision is required in pairwise comparisons.

The eigenvector method described above is now available in a software product called "Expert Choice" developed by Decision Support Software Inc. Expert Choice has been designed to facilitate the computation in AHP and to calculate the priorities for each criterion.

[3] The average consistencies for different-order random matrices may be obtained as the table below if the numerical judgments were taken at random from the scale 1/9, 1/8,... 1, 2,..., 9 [66].

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	-	-	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3.2.4.4 Synthesis

Applying the environmentally conscious requirement worksheet in this proposed framework, a judgement and pairwise comparison in the two-level hierarchy (e.g. category and criteria) will be conducted individually. Since a set of priorities will be generated along with each comparison matrix, a proper weighting process will have to be performed before obtaining the final priorities (e.g. the importance ratings in modified HOQ). This section will introduce how these priorities are related to each other and how to synthesize these priorities into the importance ratings.

Since the environmentally conscious requirements worksheet has been designed and constructed such that the components of environmental categories or criteria have no interaction between them, the assumption can be made that each level of the hierarchy is functionally independent. Based on the assumption and the AHP process, the importance ratings will be the weighted priorities from the bottom level assessments of the hierarchy structure. Using the hierarchy structure shown in Figure 3-6 as an example, the comparison matrices can be built as the following:

End-of-life management	Structure	Connection	Material	Energy	Legislation	Priorities
Structure						${}_{\text{End-of-life}}P_{\text{Structure}}$
Connection						${}_{\text{End-of-life}}P_{\text{Connection}}$
Material						${}_{\text{End-of-life}}P_{\text{Material}}$
Energy						${}_{\text{End-of-life}}P_{\text{Energy}}$
Legislation						${}_{\text{End-of-life}}P_{\text{Legislation}}$

where ${}_xP_y$ represent priorities (weights) in which subscript y are the comparison components with respect to the goal of subscript x.

Next, five comparison matrices may be built with respect to the five categories; they are:

Structure	Part consolidation	Ease of handling	Open access	Standard part	Priorities
Part consolidation					${}_{Structure}P_{Consolidation}$
Ease of handling					${}_{Structure}P_{Easy\_handling}$
Open access					${}_{Structure}P_{Open\_access}$
Standard part					${}_{Structure}P_{Standardization}$

Connection	Reduce fasteners	Detachable joining	Min. variety	Priorities
Reduce fasteners				${}_{Connection}P_{Reduce\_fasteners}$
Detachable joining				${}_{Connection}P_{Detachable}$
Min. variety				${}_{Connection}P_{Min\_variety}$

Material	Avoid metal inserts	Min. variety	Compatible	Recyclable	Priorities
Avoid metal inserts					${}_{Material}P_{Metal\_inserts}$
Min. variety					${}_{Material}P_{Min\_variety}$
Compatible					${}_{Material}P_{Compatible}$
Recyclable					${}_{Material}P_{Recyclable}$

Energy	Energy consumption on disassembly	Energy recovery	Priorities
Energy consumption on disassembly			${}_{Energy}P_{Energy\_consumption}$
Energy recovery			${}_{Energy}P_{Energy\_recovery}$

Legislation	Toxic material	Recycling enforcement	Hazardous waste	Priorities
Toxic material				${}_{Legislation}P_{Toxic\_material}$
Recycling enforcement				${}_{Legislation}P_{Recycling\_enforce}$
Hazardous waste				${}_{Legislation}P_{Hazardous\_waste}$

Finally, the overall importance ratings with respect to the criteria may be calculated by multiplying the criterion's weight with the corresponding category's weight, which is:

$$ {}_xP_z = {}_xP_y \times {}_yP_z \tag{3.1} $$

where ${}_xP_z$ represent the importance ratings for all criteria z's;

${}_xP_y$ represent the category weights with respect to the overall goal;

${}_yP_z$ represent the criterion weights with respect to the corresponding category.

3.2.5 Relationship Matrix

The function of the Relationship Matrix is to identify relationships between the environmentally conscious requirements and the alternatives of design feature. The design team will make the judgement of the strength of the relationship between environmental requirements and the potential design features, and then assign the proper relationship symbol to the intersections of each column and row.

The strength of relationship is usually determined by consensus among the design team. It is one of the most difficult and important steps in the modified HOQ approach. A failure to properly define the strength of the relationship between the environmentally conscious requirements and alternatives of design features may lead the whole project in an entirely wrong direction.

The relationships between two attributes are sometimes not physically measurable. Therefore, linguistic terms, such as "strong", "moderate" and "weak", are utilized in modeling the conventional HOQ in order to quantify unmeasurable variables. However, the use of linguistic terms may result in considerable deviation from the fact due to vague and imprecise content of the terms. It is also the weakness of QFD because of the lack of a mathematical method to precisely measure the relationships which are defined by using artificial language. The basic concept of fuzzy set theory[4], on the other hand, is designed to deal with vagueness and uncertainty. Therefore, incorporating fuzzy set theory with HOQ is an attempt to capture and quantify the evaluation terms made by artificial language. Specifically, the triangular fuzzy number, a subset of fuzzy set theory, has been chosen to model and further accomplish the analysis of the Modified House of Quality.

3.2.5.1 Linguistic Variables

Linguistic variables are utilized to quantify linguistic terms. The concept of linguistic variables was introduced by Dr. Zadeh in his published paper titled "The concept of a linguistic variable and its application to approximate reasoning" [88]. In that paper, fuzzy numbers were applied to interpret linguistic variables. For example, the linguistic term – "strong" is an approximate characterization in the statement "Easy separation of parts is strongly related to threaded fasteners." To provide the term "strong" with an exact numerical value to measure the relationship between easy separation and threaded fasteners, a specific fuzzy number should be assigned to represent the linguistic term.

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[4] The introduction of fuzzy set theory is addressed in Appendix C.

In order to convert linguistic terms or values to fuzzy numbers, several numerical approximation systems have been proposed. An eight-scale system proposed by Chen and Hwang [19] is utilized in the modified HOQ model in order to express the variables of relationships. Table 3-4 shows the relationships between linguistic terms and scales. After converting these measurement scales to triangular fuzzy numbers, the membership functions may be captured in Figure 3-9. There are no standard methods for choosing the scale. It would be a usable scale if all natures of judgement may be covered by the linguistic terms in that scale.

Table 3-4 Linguistic terms and scales (Adapted from [19])

Scale	1	2	3	4	5	6	7	8
# of terms	two	three	five	five	six	seven	nine	eleven
None								√
V. low			√		√	√	√	√
Low-v. low							√	√
Low		√	√	√	√	√	√	√
Med. low				√	√		√	
Mol low						√		√
Medium	√	√	√	√		√	√	√
Mol high						√		√
Med. high				√	√		√	
High	√	√	√	√	√	√	√	√
High-v. high							√	√
V. high			√		√	√	√	√
Excellent								√

Note: v. – "very"; med. – "medium"; mol. – "more or less"

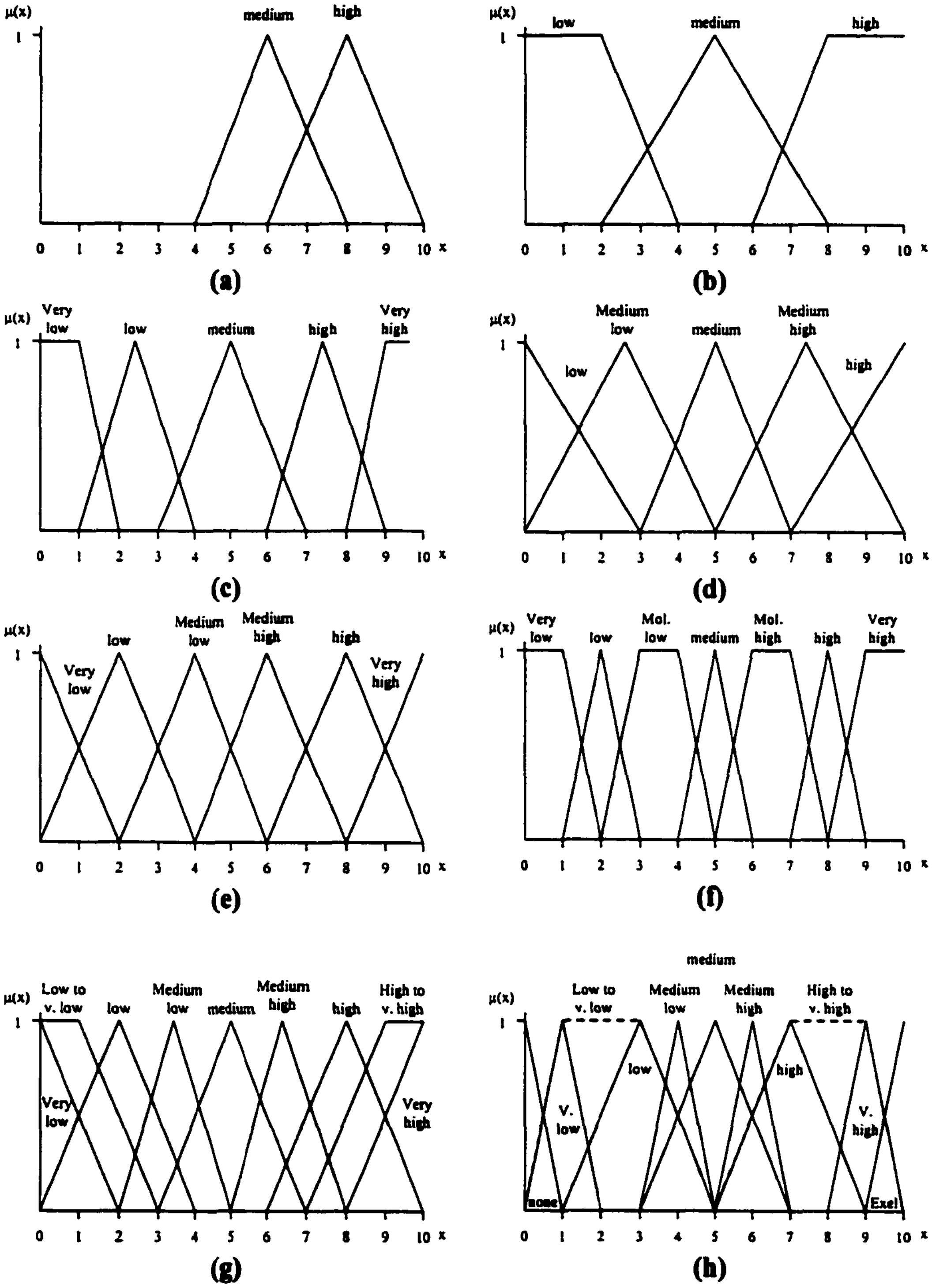


Figure 3-9 Membership functions of measurement scales (Adapted from [19])

The approximation systems shown in Figure 3-9 depict how linguistic terms may be converted to fuzzy expressions. For example, a system consisting of two linguistic terms "medium" and "high", implies the numerical meanings of close to 6 and 8, respectively. After transforming into fuzzy expressions, two membership functions can be generated as:

$$\mu_{medium}(x) = \begin{cases} 0 & x \le 4 \\ \dfrac{x-4}{2} & 4 \le x \le 6 \\ \dfrac{8-x}{2} & 6 \le x \le 8 \\ 0 & x \ge 8 \end{cases}$$

and

$$\mu_{high}(x) = \begin{cases} 0 & x \le 6 \\ \dfrac{x-6}{2} & 6 \le x \le 8 \\ \dfrac{10-x}{2} & 8 \le x \le 10 \\ 0 & x \ge 10 \end{cases}$$

Before constructing the relationship matrix in the modified HOQ, two criteria have to be decided in advance; they are (1) determining the linguistic terms and/or variables, and (2) choosing an appropriate fuzzy number to represent the corresponding linguistic variable. The first concern of determining the linguistic terms is important because it will lead designers to select the measurement scale. Considering the second criterion, the designer has to select a fuzzy number that can properly represent the behaviors of linguistic terms and can be easily handled in arithmetic operations.

Basically, there are three frequently used types of fuzzy numbers that include triangular, trapezoidal and π-function fuzzy numbers (see Appendix C). Since the triangular fuzzy number has the simplest arithmetic operations (see section 3.2.6), it has been selected to model the linguistic variables in this thesis.

There are two approaches to determine the measurement scale. One of the approaches is selecting the linguistic terms first and then finding the corresponding numerical values and membership functions. The other one is to prepare a suitable numerical scale in advance, then to find an approximation system that may represent the numerical scale completely.

In the first approach, if the designers determine to use the terms "low", "medium" and "high", the choice of Scale 2 should be assigned for transforming linguistic terms to fuzzy numbers. Even though all the scales except Scale 1 are available to interpret these three terms (refer to Table 3-4 and Figure 3-9), the simplest scale, i.e. Scale 2, should be selected.

The second approach would be used when a numerical scale has been selected in advance. For example, the weighting scale of 1, 3 and 9 is frequently adopted in conventional HOQ. When the scale is applied in the modified HOQ approach, it has to be transformed into fuzzy expressions. Looking for appropriate fuzzy membership functions from the figure of membership functions of measurement scales, Scale 8 should be selected as the approximation system because it is the only one that covers all values used in the weighting scale.

3.2.5.2 Symbols in The Relationship Matrix

The cells in the relationship matrix represent the correlation between environmental requirements and alternatives of design features. When linguistic terms and associated fuzzy numbers have been determined, the design team may start with assigning relationship strengths into every intersection of the relationship matrix. In order to make the relationship matrix understandable and readable, symbols have been used to represent the strength of relationship.

Some special symbols are utilized in traditional HOQ, such as using "⊙" for strong relationship, "O" for moderate relationship and "▲" for weak relationship. In the modified HOQ approach, the symbols of relationship will be recorded in terms of the base interval of triangular fuzzy numbers. The use of a triangular fuzzy number base interval may provide us a unique system to interpret the level of relationship as well as facilitate the computation process of Absolute Scores (also refer to section 3.2.6).

For the special shape membership function, triangular fuzzy numbers, the base interval can be denoted as the triple [a, m, b] (shown in Figure 3-10). The points a and b are the intersections of the membership function and X-axis, while point m has the unity of membership function.

For example, a three levels weighting system with numerical values of 1, 3 and 9 will have the base intervals of [0, 1, 2], [1, 3, 5] and [8, 9, 10], respectively (refer to Figure 3-9). After making judgements on the relationships by using the three-level scale, the relationship matrix may have an appearance similar to Figure 3-11.

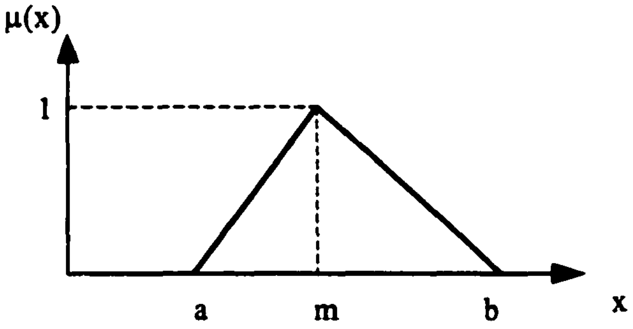


Figure 3-10 The base interval of triangular fuzzy numbers

	Threaded fastener	Nonthreaded fastene	Welding	Adhesive
Easy separation of parts	[8, 9, 10]	[8, 9, 10]	[0, 1, 2]	[0, 1, 2]
Minimization of material varieties	[1, 3, 5]	[0, 1, 2]	[8, 9, 10]	[0, 1, 2]
Enabling simultaneous disassembly	[8, 9, 10]	[0, 1, 2]	[1, 3, 5]	[1, 3, 5]
Protecting assembly groups from corrosion	[1, 3, 5]	[1, 3, 5]	[0, 1, 2]	[8, 9, 10]

Figure 3-11 Symbols in the relationship matrix

3.2.6 Absolute Scores

In previous sections, the linguistic judgements have been properly fuzzified. As mentioned earlier, the purpose of the fuzzification is to translate input variables that are defined by linguistic expressions into more realistic fuzzy approximations. In this section, the computation of Absolute Scores will be introduced. Since linguistic variables are involved, the arithmetic operations on fuzzy numbers will be the basis of calculating Absolute Scores. The addition and multiplication of fuzzy numbers will be used for performing the computation of Absolute Scores.

3.2.6.1 Arithmetic Operations on Fuzzy Numbers

The arithmetic operations of fuzzy numbers are based on their α-cuts (i.e. arithmetic operations on closed intervals). The operations of addition and multiplication will be used for modeling the modified HOQ. Specifically, the following equations are defined by using the interval of confidence proposed by Kaufmann and Gupta [43].

The interval of confidence provides a way to describe the quality aspects of how fuzzy number $\tilde{A}$ exists at an arbitrary α-cut level in the range a_1 to a_2 as illustrated in Figure 3-12. The range of a_1 to a_2, called $\tilde{A}$'s interval of confidence, is stated as $\tilde{A} = [a_1, a_2]$.

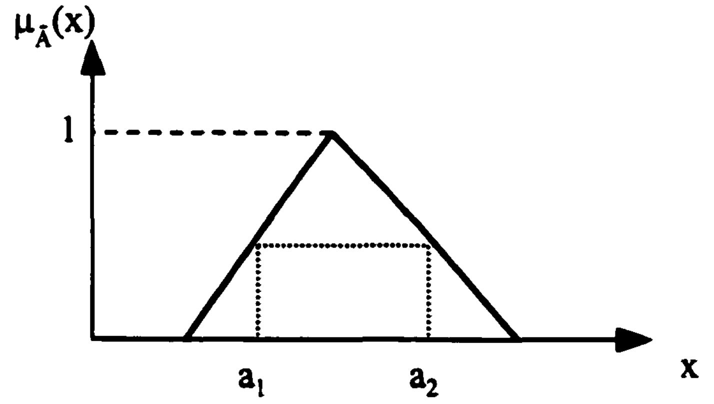


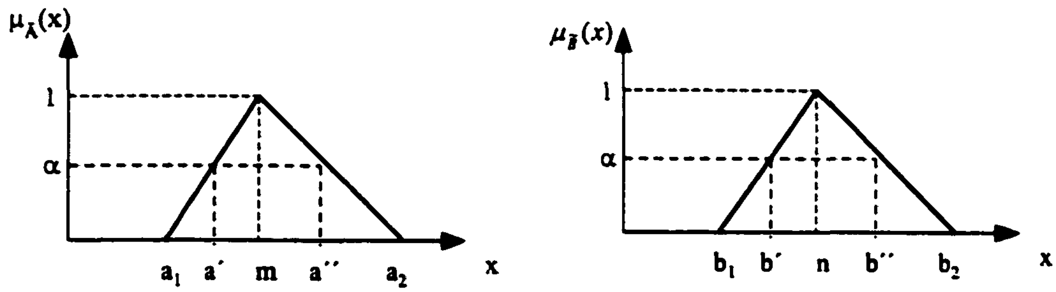
Figure 3-12 Interval of confidence

Let $\tilde{A}$ and $\tilde{B}$ be two triangular fuzzy numbers, and their base intervals are $[a_1, m, a_2]$ and $[b_1, n, b_2]$ respectively, as illustrated in figures below. The membership functions of $\tilde{A}$ and $\tilde{B}$ will then be established as:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x \le a_1 \\ \dfrac{x-a_1}{m-a_1} & a_1 \le x \le m \\ \dfrac{a_2-x}{a_2-m} & m \le x \le a_2 \\ 0 & x \ge a_2 \end{cases}$$

and

$$\mu_{\tilde{B}}(x) = \begin{cases} 0 & x \le b_1 \\ \dfrac{x-b_1}{n-b_1} & b_1 \le x \le n \\ \dfrac{b_2-x}{b_2-n} & n \le x \le b_2 \\ 0 & x \ge b_2 \end{cases}$$



The arbitrary level of α-cut for fuzzy numbers $\tilde{A}$ and $\tilde{B}$ will be obtained as:

$$A^{\alpha} = [a', a'']$$

$$\alpha = \begin{cases} \dfrac{a'-a_1}{m-a_1} \Rightarrow a' = (m-a_1)\alpha + a_1 \\ \dfrac{a_2-a''}{a_2-m} \Rightarrow a'' = -(a_2-m)\alpha + a_2 \end{cases}$$

and

$$B^{\alpha} = [b', b'']$$

$$\alpha = \begin{cases} \dfrac{b'-b_1}{n-b_1} \Rightarrow b' = (n-b_1)\alpha + b_1 \\ \dfrac{b_2-b''}{b_2-n} \Rightarrow b'' = -(b_2-n)\alpha + b_2 \end{cases}$$

$$\begin{aligned} A^{\alpha} + B^{\alpha} &= [a', a''] + [b', b''] \\ &= [(m+n-a_1-b_1)\alpha + (a_1+b_1),\ \ -(-m-n+b_2+a_2)\alpha + (a_2+b_2)] \end{aligned}$$

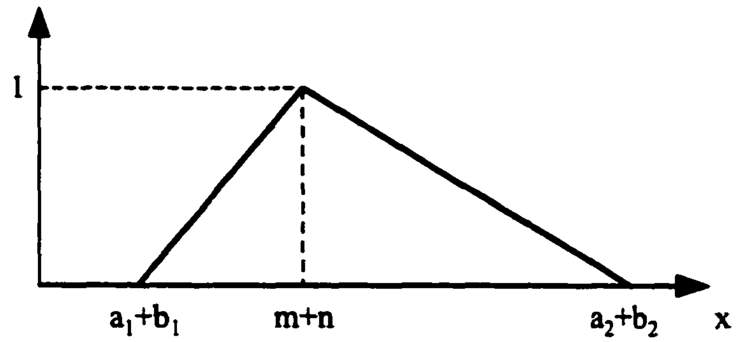
therefore,

$$\mu_{\tilde{A}+\tilde{B}}(x) = \begin{cases} 0 & x \le a_1+b_1 \\ \dfrac{x-(a_1+b_1)}{(m+n-a_1-b_1)} & a_1+b_1 \le x \le m+n \\ \dfrac{-x+(a_2+b_2)}{(a_2+b_2-m-n)} & m+n \le x \le a_2+b_2 \\ 0 & x \ge a_2+b_2 \end{cases}$$

As a result, in terms of the base intervals, the addition of triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$ may be derived as:

$$\begin{aligned} \tilde{A} + \tilde{B} &= [a_1, m, a_2] + [b_1, n, b_2] \\ &= [a_1+b_1, m+n, a_2+b_2] \qquad (3.2) \end{aligned}$$

The following figure shows the result from the additive operation of triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$.



The same method may be applied for verifying the multiplication of triangular fuzzy numbers. The fuzzy number $\tilde{A}$ multiplied by a constant k and by fuzzy number $\tilde{B}$ may be derived as equation (3.3) and (3.4), respectively.

$$\begin{aligned} k \cdot \tilde{A} &= [k, k, k] \cdot [a_1, m, a_2] \\ &= [k \cdot a_1, k \cdot m, k \cdot a_2] \end{aligned} \tag{3.3}$$

$$\begin{aligned} \tilde{A} \cdot \tilde{B} &= [a_1, m, a_2] \cdot [b_1, n, b_2] \\ &= [a_1 \cdot b_1, m \cdot n, a_2 \cdot b_2] \end{aligned} \tag{3.4}$$

3.2.6.2 Computation of Absolute Scores

Once the importance ratings and the degrees of relationships have been decided, the Absolute Scores can be calculated by summing the values of each column of the relationship multiplied by the relative importance rating. Even though the computation of Absolute Scores is quite straightforward, difficulties such as the use of both crisp numbers and fuzzy numbers have to be dealt with before the conclusion may be drawn.

If only considering crisp numbers, presenting in mathematical formula, for each column, j, the absolute score (AS) can be obtained by:

$$AS_j = \sum_{i=1}^{n} \left(W_i * R_{ij} \right) \tag{3.5}$$

where

W_i = importance ratings,

R_{ij} = values of relationship.

Since fuzzy numbers are involved, the equation (3.5) has to be revised by substituting R_{ij} with triangular fuzzy numbers. As mentioned earlier, the arithmetic operations of triangular fuzzy numbers may be based on their interval of confidence and denoted as their base intervals. Therefore, in the modified HOQ approach, the formula for calculating Absolute Scores will be defined as:

$$\begin{aligned} AS_j &= [as_{1j}, as_{mj}, as_{2j}] \\ &= \sum_{i=1}^{n} \left\{ w_i \cdot \left[r_{1ij}, r_{mij}, r_{2ij} \right] \right\} \\ &= \sum_{i=1}^{n} \left\{ w_i \cdot r_{1ij}, w_i \cdot r_{mij}, w_i \cdot r_{2ij} \right\} \end{aligned} \tag{3.6}$$

where

w_i = importance ratings,

$[r_{1ij}, r_{mij}, r_{2ij}]$ = base intervals of fuzzy relationship.

The Absolute Scores obtained by using equation (3.6) are fuzzy numbers. For assigning the priority ranks among alternatives of design features, the Absolute Scores have to be transformed back to crisp numbers. The transforming process is called defuzzification and it is addressed in section 3.3.3.2.

3.3 Systematic Analysis

This section will introduce the second part of the proposed green product design framework – systematic analysis. The systematic approach will synthesize the individual analyses made by the modified HOQ. Essentially, this process of analysis is the product life cycle approach that takes into consideration the entire life cycle of a product starting from raw material extraction and ending with end-of-life product management. In other words, the tasks incorporated in a product life cycle include mining, material processing, manufacture and assembly, use, and disposal. In addition, the transportation of materials between each pair of the life-cycle stages should also be considered.

The proposed framework is an up-front design tool that considers all the product life-cycle stages simultaneously for the design and production of environmentally friendly products. The purpose of using this systematic approach is to evaluate all alternatives of design features by synthesizing the environmental influences in all the product life cycle stages.

The systematic analysis encompasses two phases: (1) life cycle design approach, and (2) overall assessment [78]. In phase one, the product life cycle is divided into four stages. The modified HOQ will be performed in every product life-cycle stage in order to obtain the relative preference rankings with respect to alternatives of design features. In phase two, the results from each modified HOQ analysis will be synthesized by applying the AHP. Figure 3-13 shows the arrangement of the two phases.

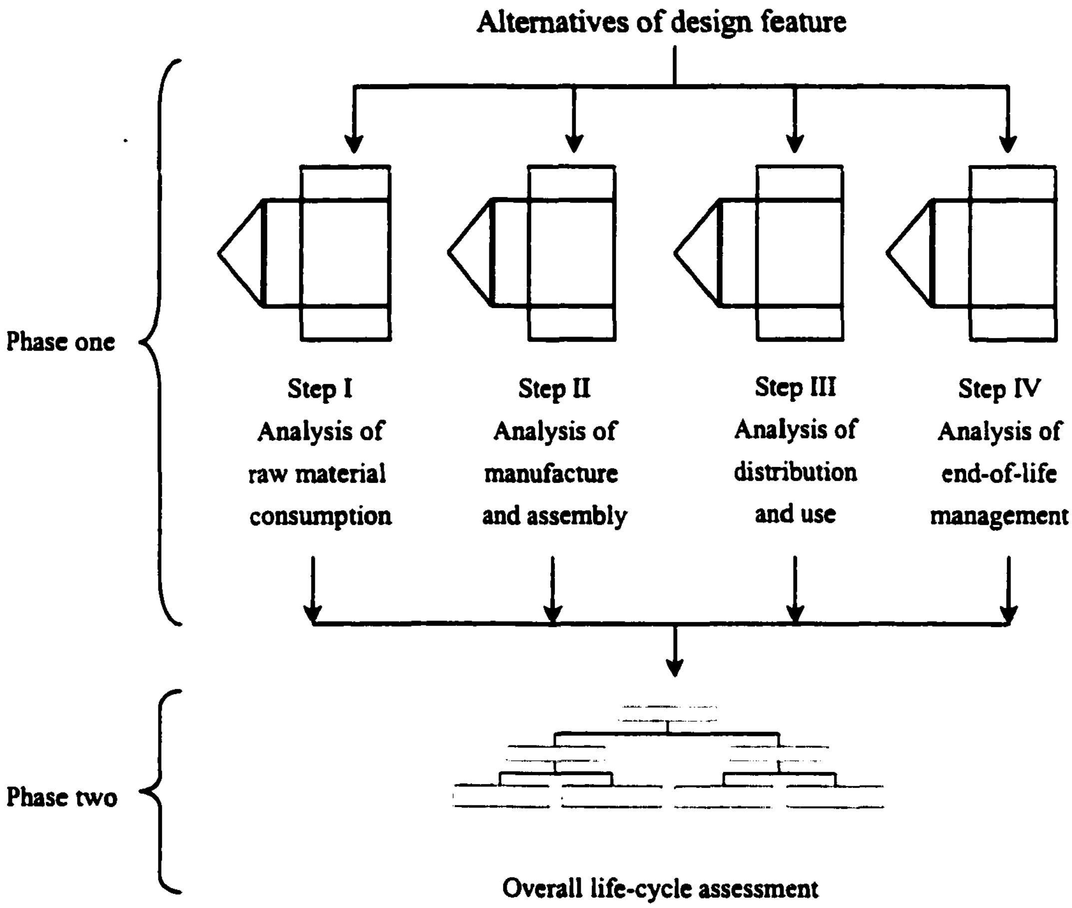


Figure 3-13 Two phases arrangement

3.3.1 Life Cycle Design Approach

A product life cycle is organized into four stages in this proposed framework. Figure 3-14 presents the physical flow of the product life-cycle stages, which include:

- raw material extraction and processing;
- manufacture and assembly;
- use and distribution; and
- product end-of-life management.

Raw material extraction means mining nonrenewable material from the earth. These materials usually need to be further processed into base materials by means of separation and purification. In addition to extraction from the earth, designers should count on other sources of raw materials as an input of this stage, which are recycled materials.

The second product life-cycle stage in the proposed framework is product manufacturing and assembling. In this stage, parts will be produced through a number of fabrication processes. Afterwards, the parts will be assembled into the final product and then released to the consumer market.

Distribution and use is considered as the third product life-cycle stage. The logistic design and packaging design are two major aspects with respect to product distribution. For product usage, designers should always keep in mind energy consumption and durability.

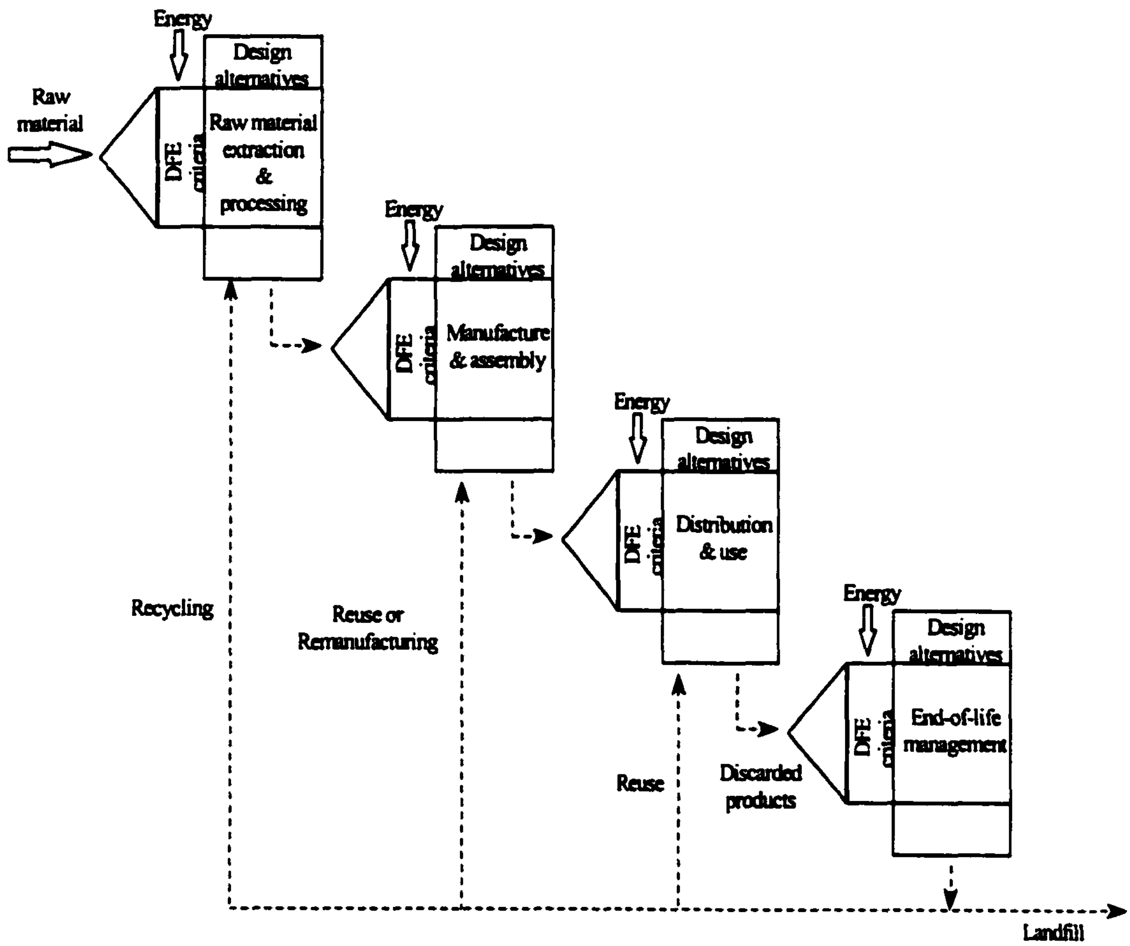


Figure 3-14 Life cycle design diagram

The last stage in the product life cycle is the product end-of-life management. After a certain time period of use, products will finally be discarded. In addition to dumping post-consumer products into landfills, there are at least three alternative strategies for dealing with end-of-life products. These three strategies are reuse, remanufacture and recycle. Reused and remanufactured parts would be returned to associated manufacturing facilities (e.g. either the second stage – "manufacture and assembly" or the third stage – "distribution and use") for restarting another life cycle. Recycled materials, on the other hand, would be either reprocessed into base materials for the use of another product life cycle, or incinerated to retrieve the energy from the materials.

3.3.2 The Role of Modified HOQ

Using a series of modified HOQ matrices, as shown in Figure 3-13, can perform the concept of product life cycle design. The following discussion will describe how a series of matrices can enable the designers to capture the overall performance of a specific design feature throughout its whole life span.

The evaluation of the alternatives of design feature will be performed in four modified HOQ matrices. Each modified HOQ matrix has its own environmentally conscious requirements, while the objects to be analyzed (e.g. alternatives of design features) remain the same. The relationships between environmental concerns and design alternatives can be identified by using the modified HOQ method. Therefore, if environmentally conscious requirements can be developed properly, the results generated from the four modified HOQ matrices will be an index representing the preference of alternatives of design features.

3.3.2.1 Analysis of Raw Material Consumption

The focus of this step of analysis is on the first product life-cycle stage - raw material consumption. It attempts to capture the relationships between environmental aspects and the production requirements with respect to the raw material consumption and processing stage.

This step of analysis will begin with a survey of material requirements. In essence, it may be looked at in two ways, which are direct requirements and indirect requirements. Direct requirements consist of the mass of material consumption and relevant energy used for material processing, while indirect requirements will consider the by-product of the whole material acquisition process.

With respect to the mass of material consumption, the associated environmental considerations will at least include natural resources depletion and recyclability. During the process of material processing, some hazardous chemical substances will have to be added. Based on the principles of Design for Environment, the criterion of how to minimize the risk to the environment resulting from use of hazardous materials should be addressed. Residue management, such as minimizing process wastes including air emissions, liquid effluents, and hazardous and nonhazardous solid wastes, is also within the system boundary of the product life-cycle stage of raw material consumption.

While the design team finishes this step of modified HOQ analysis, the results will indicate the preference of the alternatives of design feature under the constraints in the raw material consumption stage. These results will be used for the following overall assessment.

3.3.2.2 Analysis of Manufacture and Assembly

This step of analysis focuses on the product life-cycle stage of manufacture and assembly. As shown in Figure 3-13, the input elements include reused or remanufactured parts from the recycling of disposed products, and related material/energy consumption. The outputs are the finished goods.

Within the boundary of this step of analysis, issues to be considered for product design will encompass Design for Assembly (DFA), and Design for Manufacturing (DFM). With respect to DFA and DFM, cost concern and operation efficiency always have higher priority than other design factors. However, the complexity of decision making is dramatically increased when environmental issues become part of the product design constraints.

For instance, consider adhesive bonding as one of the fastening alternatives. Its advantages in terms of DFA are uniform stress distribution, seal against many environments, smooth joint contours, prevention of galvanic corrosion between dissimilar materials, and it is cheaper than mechanical fastening. However, on the DFE point of view, it has limited advantages because adhesives often contain solvents which would be harmful to the environment.

3.3.2.3 Analysis of Use and Distribution

In this life-cycle stage, finished goods will be transported from manufacturing sites to distributors. Finally, products will be sold to customers for providing a service or for fulfilling a specific customer need.

During distribution and display on the shelf, packaging products will be made for providing protection and for aesthetic purposes. On the other hand, the packaging process will also generate a significant material waste. In this step of analysis, the design of the package is part of the considerations.

At the product use stage, energy consumption is the major concern, especially for electric appliances and automobiles. After a certain time of usage, the product might need some minor maintenance or repair. Therefore, design for serviceability is another subject that designers should take into consideration. In fact, there are some similarities between design for serviceability and design for disassembly, since partial disassembly might be unavoidable when maintaining or repairing a product.

Another modified HOQ analysis may be undertaken when the environmentally conscious requirements have been developed under the established boundary. The results will show the favored design alternative with respect to the life-cycle stage of use and distribution.

3.3.2.4 Analysis of End-of-life Management

All products will eventually get to the end-of-life stage when customers decide to retire the products. The strategies of a product end-of-life management include product reuse, part remanufacturing and material recycling. Hence, the inputs in this step of analysis are end-of-life products, energy required for disassembling these products, and energy required for sorting the disassembled materials and parts. The outputs are reusable or remanufacturable subassemblies and parts, recyclable materials, and associated residuals generated from the disassembly processes.

Regarding environmental concerns, the design for product retirement should be aimed at the product end-of-life management strategies of reuse, remanufacturing and recycling. For achieving any one of the goals of these strategies, the product disassembly must be accomplished (as depicted in Figure 2-3). Therefore, design alternatives should always promote ease of disassembly.

The majority of environmental problems results from the residuals generated within the life-cycle stage of the end-of-life product. The rising level of municipal solid waste has caused a landfill site shortage. Many industries such as the auto and electronic appliance industries have started to develop new design concepts for adapting to the changing environmental requirements. This step of analysis evaluates design alternatives so that end-of-life products can be enhanced to secure the goals of reuse, remanufacture and recycle.

3.3.3 The Overall Assessment

The overall assessment is the second phase of the proposed framework. It involves bringing together the results of the previous four modified HOQ matrices and then evaluating the overall performance of the alternatives of design feature throughout the entire product life cycle.

When conducting the modified HOQ analysis, designers consider only the environmental criteria within a single life-cycle stage. The absolute scores obtained from each modified HOQ analysis represent the preference weightings with respect to the specific product life-cycle stage. The proposed overall assessment will provide a means to synthesize the four steps of analysis and calculate the overall weightings. For example, the material used for automobile fenders may have two design alternatives which are plastic and steel fenders. When considering the use stage, plastic fenders might gain higher weights because it would increase the ratio of miles-per-gallon due to mass reduction. On the other hand, steel fenders may be preferred for the end-of-life management stage due to the recyclability. The final decision will have to rely on the overall scores that may be obtained by using the method described in the following sections.

3.3.3.1 The Overall Scores

The overall scores will provide designers an index that shows the weightings of design alternatives with respect to the overall goal – "green product design." Since there are four stages in the life-cycle design approach, the overall score may be obtained by using equation (3.7) that is the summation of the absolute score multiplied by the associated weight of life-cycle stage.

$$OS_j = \sum_{i=1}^{4} AS_{ij} \times W_i \qquad (3.7)$$

where

OS_j = Overall Score with respect to the jth design alternative;

AS = Absolute Score;

W_i = Weight of ith life-cycle stage.

In equation (3.7), the absolute score is one of the variables that may be calculated by using (3.6). As stated in section 3.2.4, using AHP will allow the capture of a rational weight. Therefore, AHP has been proposed as a method for determining the weight of life-cycle stage. By applying AHP, a comparison matrix will be constructed first that is as follows:

Green Product Design	Raw mtl consumption	Mfg & assembly	Use & distribution	End-of-life management	Weights
Raw mtl consumption					W_1
Mfg & assembly					W_2
Use & distribution					W_3
End-of-life management					W_4

Followed by pairwise comparison, the weights (W_i) for life-cycle stages can be calculated.

3.3.3.2 Defuzzification

Since the results obtained from (3.6) and (3.7) are fuzzy numbers, they have to be converted to so-called "crisp" numbers in order to make comparisons of the alternatives of design feature and to place the priority ranks. The process of converting a fuzzy number to a single real number is called defuzzification.

Yager's Centroid method [47][49][86] has been selected as the defuzzification method in this proposed framework. This method is to find the geometric center of a fuzzy number, corresponding to an x value on the horizontal axis (see Figure 3-15).

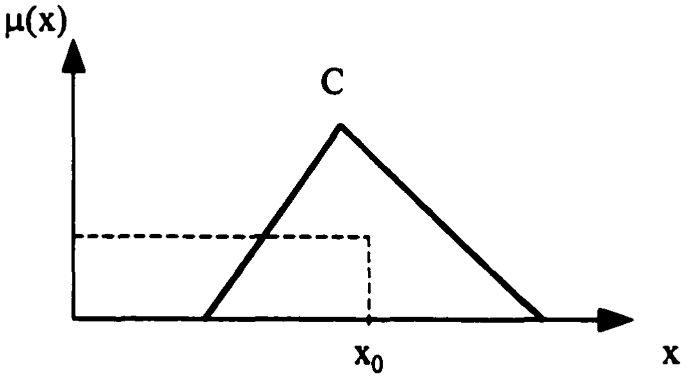


Figure 3-15 Centroid point of fuzzy number C

The following equation (3.8) is used to calculate the Centroid point x_0 [86].

$$x_0 = \frac{\int_c x \cdot \mu_C(x) dx}{\int_c \mu_C dx} \qquad (3.8)$$

By applying equation (3.8), the overall scores calculated from employing equation (3.7) could be transforming into crisp numbers. Accordingly, these crisp overall scores can be compared and ranked. The highest rank will be assigned to the alternative of design feature that has the largest "crisp" overall score.

Two illustrated examples, namely, fuel tank analysis and fastener selection, are presented in chapter 4 and 5, respectively. The fuel tank analysis example will demonstrate the proposed green product design framework for selecting the environmentally friendly material. The case study of fastener selection will provide designers with a general guide to selecting a proper joining method.

Chapter 4 Analysis of Plastic And Steel Fuel Tanks

4.1 Introduction

This chapter will illustrate the proposed green product design framework with the analysis of plastic fuel tanks and steel fuel tanks. In the automotive industry, steel and thermoplastic are two materials that are currently utilized for producing fuel tanks. These two materials have quite different performances in each stage of the product life cycle. The proposed framework provides the design team an analysis tool for fully understanding the two materials throughout the fuel tank life cycle.

Since the plastic fuel tank is gradually replacing the traditional use of steel fuel tank and environmental concerns have dramatically affected the product design concept, two studies [3][45] related to fuel tank systems have been found. These two studies were focused on the Life Cycle Assessment of fuel tanks, especially for the Life Cycle Inventory analysis. Even though these two studies have done quantitative data collection, debate always centers around the accuracy of the data. For example, the data of energy consumption for producing 1 kilogram HDPE (High Density Polyethylene) is 80.98 MJ in [45] and 65.47 MJ in [3]. The almost twenty-five percent variance might lead the analyses to draw totally different conclusions.

The proposed green product design framework uses the qualitative pairwise comparison instead of quantitative data collection. Therefore, it is expected that the weakness of using the methodology of Life Cycle Assessment will be improved.

4.2 Boundaries of Life-cycle Stages

The proposed framework will start with the determination of the boundaries of Life-cycle stages. Following the concept of life-cycle design, the fuel tank life cycle may be classified into four stages: raw material consumption, manufacture and assembly, use and distribution, and end-of-life management. The use of a mass flow diagram may enhance defining the boundaries of the four stages, which is shown as Figure 4-1 and 4-2. Note that in the mass flow diagram the solid line represents the mass input and the dotted line represents the mass output.

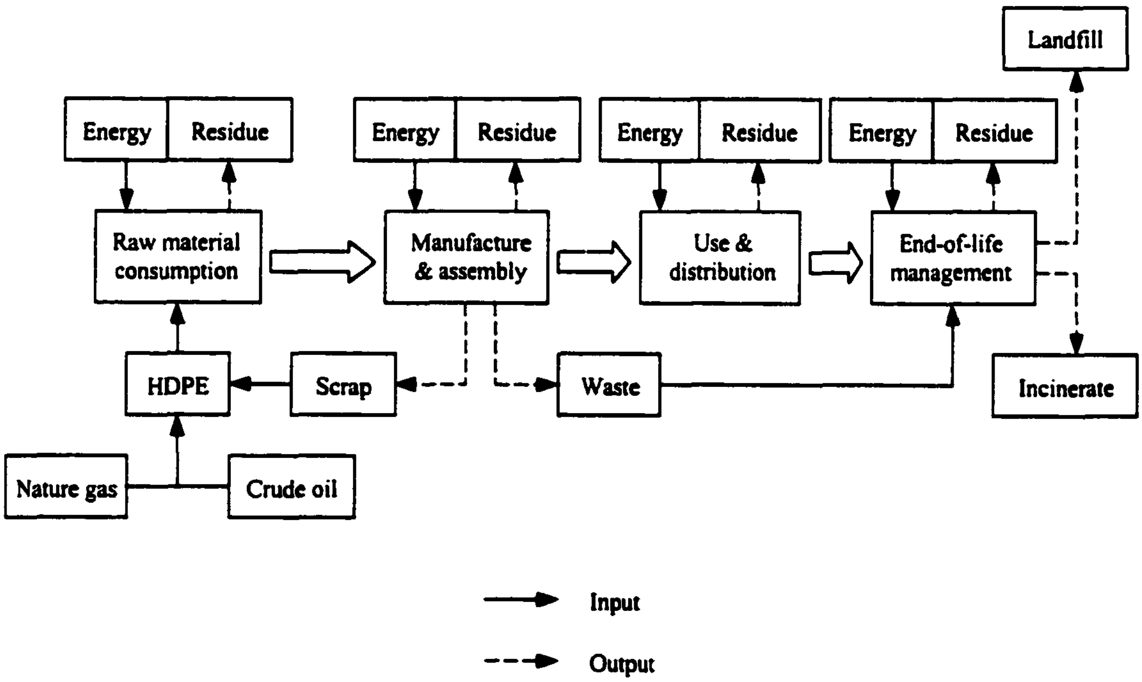


Figure 4-1 Mass flow diagram of a plastic fuel tank

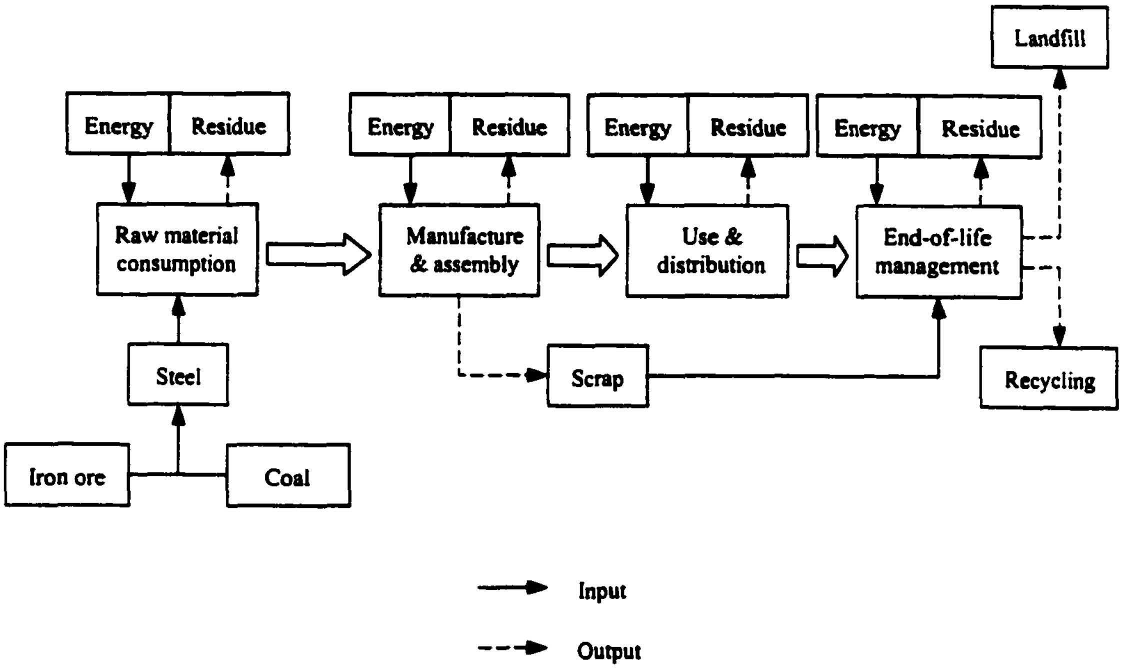


Figure 4-2 Mass flow diagram of a steel fuel tank

4.3 Environmentally Conscious Requirements

After confirming the boundaries of analysis, the design team can discover the associated environmentally conscious requirements by using the proposed worksheets (Figure 3-2).

Four worksheets will be used for generating the environmentally conscious requirements with respect to the comparison of fuel tanks. As identified in Table 3-2, there are three categories for the raw material consumption stage, while there are five categories for the other life-cycle stages. Assumptions have been made for facilitating the undergoing analysis including: (1) plastic fuel tank production will use HDPE only; (2) steel fuel tank production will use carbon steel only; (3) the transportation cost is neglected.

Based on the above assumptions, design criteria may be generated and recorded in the worksheet as shown below. The specific environmental laws have not been pointed out under the legislation category. Instead, the emissions are listed, since they might be against the relevant regulations.

Raw material extraction

Category	Material	Energy	Legislation
Criteria	• Deposit on earth • Renewable resource	• Efficient material processing	• Air emissions • Solid waste • Water effluents

In the life-cycle stage of manufacture and assembly, raw material (e.g. HDPE and carbon steel) will be transformed into the finished fuel tank. The manufacturing processes may be expressed as the following process flow diagrams.

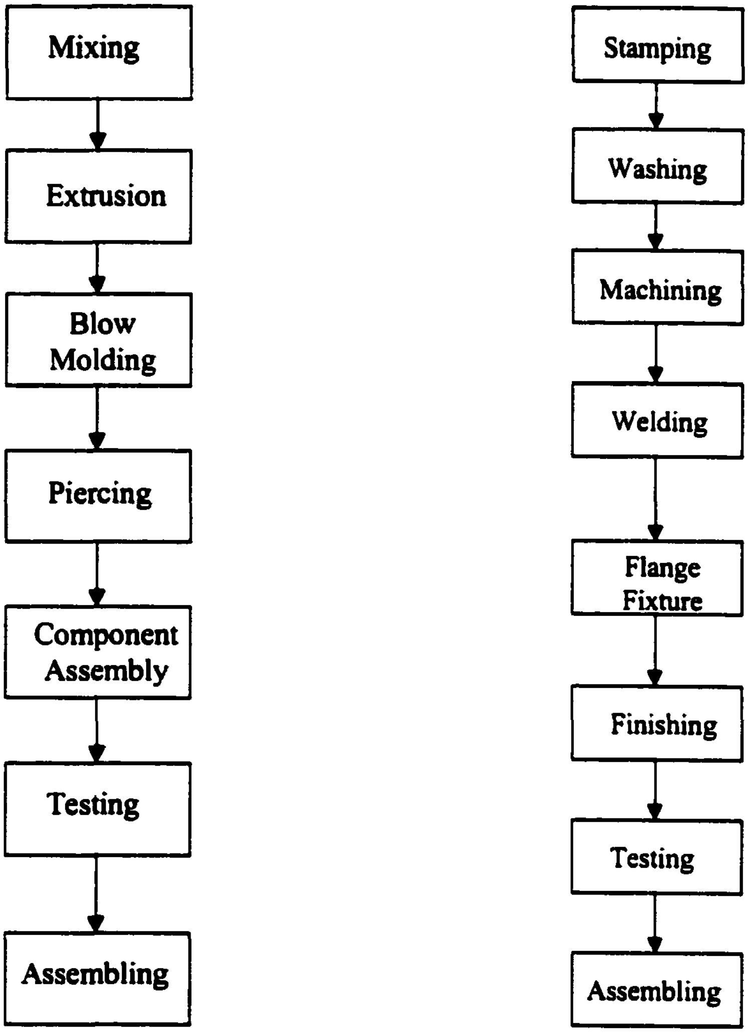


Figure 4-3 Fuel tanks manufacturing process flow diagram

The production process of plastic fuel tanks has shown that the energy intensive operations include blow molding and fuel sender unit assembling. In comparison, steel fuel tanks need energy for stamping, welding and flange forming. A critical issue under the material category is the scrap rate. Because of the limitation of production technologies, both models of fuel tank have a certain defect rate. For dealing with the defects, extra energy will be used and materials will be wasted. Therefore, the average scrap rate is an important index of making the judgement. Some criteria have been identified with respect to the established five categories. The following worksheet shows the categories and the corresponding criteria.

Mfg. & assembly

Category	Structure	Connection	Material	Energy	Legislation
Criteria	• Modular design • Ease of handling	• Components assembly • Assemble onto vehicle	• Less scrap rate • Molded-in color • Minimize material variety	• Economy production energy	• Emissions

In the use stage, the fuel tanks' performance of lifetime usage and maintenance will be analyzed. The plastic fuel tank is up to 30% lighter than a steel fuel tank. This implies that a plastic fuel tank has less energy consumption than a steel fuel tank during its lifetime usage, since the energy consumed for carrying the tank itself will be reduced if it has a lighter weight. Some other factors, such as corrosion resistance and the requirement of a coating are encompassed in this stage's considerations. The following worksheet contains the parameters that will be used for the modified HOQ analysis.

Use

Category	Structure	Connection	Material	Energy	Legislation
Criteria	• Fuel carry capacity • Walls thickness	• Ease of replacing fuel sender unit	• Coating • Fatigue	• Fuel economy	• Evaporative and tailpipe emissions

The main concern in the end-of-life management stage is the 3-R (reuse, remanufacturing, recycling) strategies. Basically, 100% recycling is technically achievable for steel fuel tanks. On the other hand, the plastic fuel tank will end up in the landfill because they are not economically recyclable. However, plastic fuel tanks have greater chances than steel fuel tanks for re-use when the vehicle reaches its end-of-life. The criteria used in this stage's modified HOQ analysis are provided in the following worksheet.

End-of-life management

Category	Structure	Connection	Material	Energy	Legislation
Criteria	• Standardization	• Ease of dismantling	• Recyclable • Re-usable	• Economy shredding process	• Landfill • Emissions

4.4 Importance Ratings

The computation of importance ratings starts with a two-level pairwise comparison in this illustrated fuel tank analysis case. Figure 4-4 shows the first life-cycle stage pairwise comparisons that include comparing categories in pairs with respect to the goal of raw material consumption and comparing criteria in pairs with respect to the goal of corresponding category. Since there is only one dependent of the category, "energy", it means that there is no further comparison matrix needed. Indeed, the criterion, "efficient material processing", will inherit the weights directly from the category, "energy".

Goal: Raw material consumption	Material	Energy	Legislation
Material	--	1/2	2
Energy	2	--	3
Legislation	1/2	1/3	--

(a)

Material	Deposit on earth	Renewable resource
Deposit on earth	—	1/3
Renewable resource	3	—

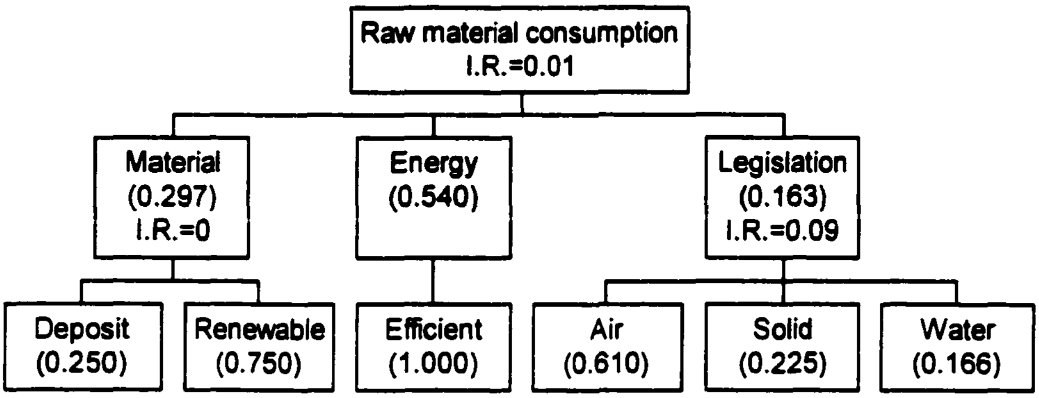
(b)

Legislation	Air	Solid	Water
Air	—	2	5
Solid	1/2	—	1
Water	1/5	1	—

(c)

Figure 4-4 Pairwise comparison matrices in the first life-cycle stage

The individual weights before synthesis are calculated as shown in the following tree diagram.

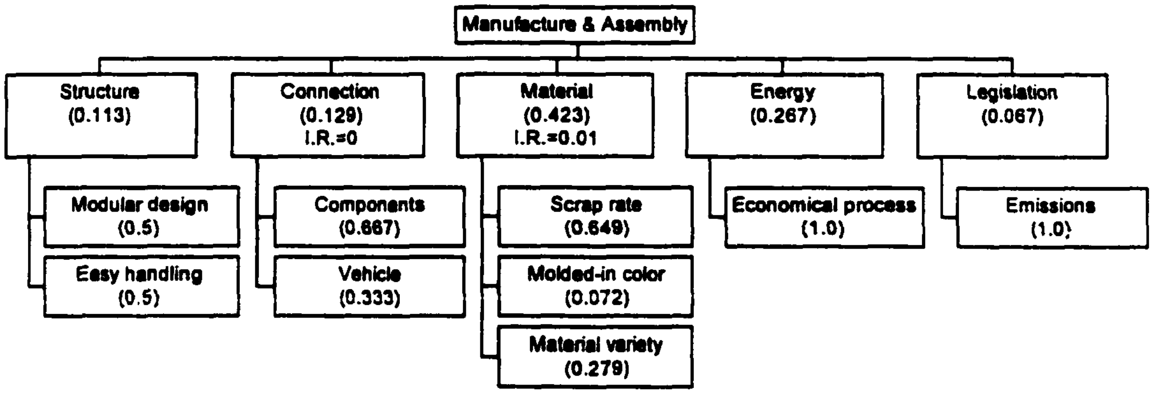


Using the equation (3.1) to synthesize the two levels hierarchy, the importance ratings for each criteria in the raw material consumption stage can be obtained as the following table.

Raw Material Criteria	Deposit on earth	Renewable resource	Efficient material processing	Air emissions	Solid waste	Water effluents
Importance ratings	0.074	0.223	0.540	0.100	0.037	0.027

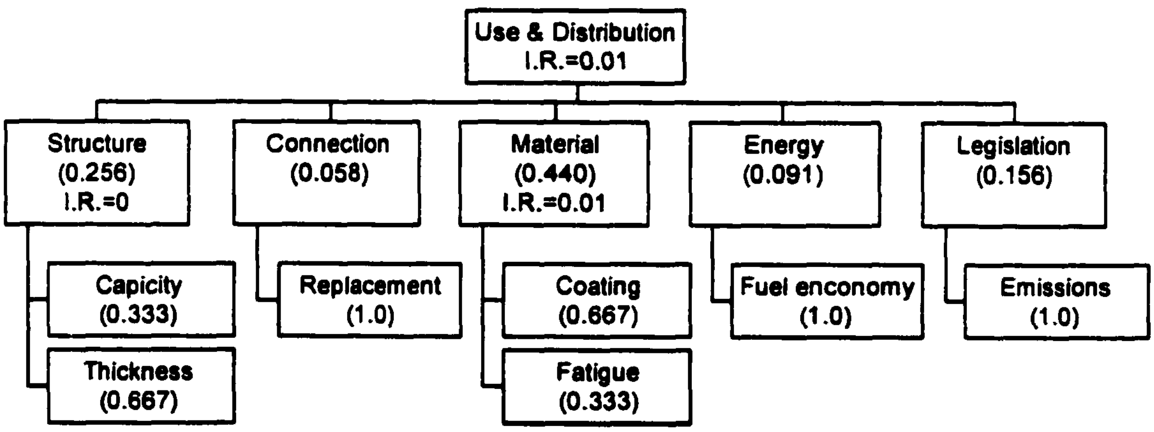
The same process will be followed for calculating all other criteria's importance ratings in the manufacture & assembly, use & distribution, and end-of-life management life-cycle stages. The results are provided as follows.

Stage II – Manufacture & Assembly



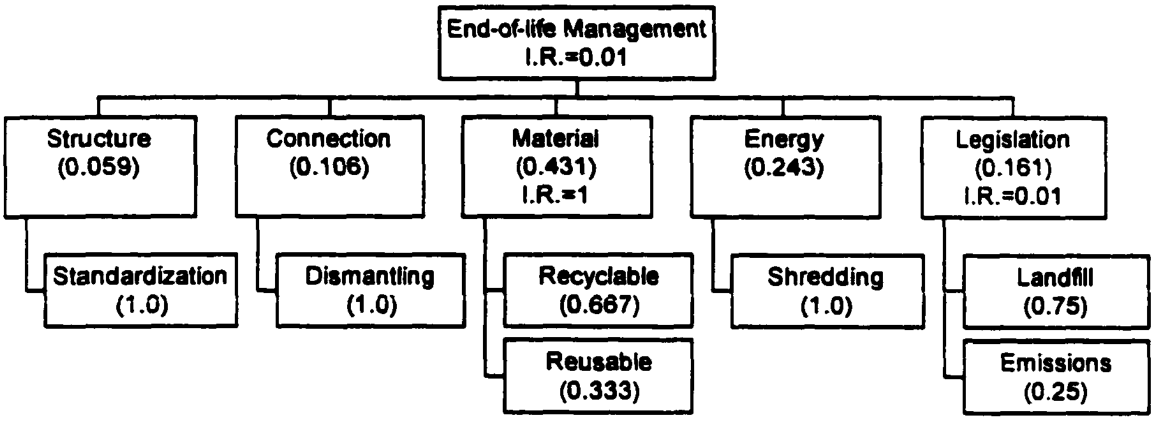
Mfg. criteria	Modular	Handling	Component	Vehicle	Scrap	Molded-in	Variety	Economy	Legislation
Rating	0.057	0.057	0.086	0.043	0.275	0.030	0.118	0.267	0.067

Stage III – Use & Distribution



Use criteria	Capacity	Thickness	Replacement	Coating	Fatigue	Fuel	Emission
Rating	0.085	0.171	0.058	0.293	0.147	0.091	0.156

Stage IV – End-of-life Management



End-of-life criteria	Standardization	Dismantling	Recycle	Reuse	Shredding	Landfill	Emissions
Rating	0.059	0.106	0.287	0.144	0.243	0.121	0.040

4.5 Relationships

Initially, the scale used for defining relationships has to be determined. The numerical scale {1, 3, 9} is selected in this fuel tank analysis, which is the most frequently used scale in the traditional HOQ approach. The linguistic meanings of the scale imply that "1" has a weak relationship, "3" has a moderate relationship and "9" has a very important relationship. After converting the selected numerical scale to fuzzy numbers, in terms of fuzzy number expression (as described in section 3.2.5.2), the selected scale will be recorded as {[0, 1, 2], [1, 3, 5], [8. 9. 10]}.

The analysis background of the fuel tanks is summarized in Table 4-1. It will be used for later relationship determination. The information contained in Table 4-1 is a qualitative description instead of quantitative data. It encompasses most of the important issues in the analysis of fuel tanks. Compared with quantitative data collection, Table 4-1 has the advantages of timesaving and easy expansion.

Using the importance ratings obtained from the previous section, the four individual modified HOQ analyses with respect to four life-cycle stages have been done and presented in Table 4-2 to Table 4-5. The results from the individual modified HOQ analysis will be used in the final synthesis analysis. The final analysis is addressed in the following section.

Table 4-1 Summary of plastic and steel fuel tanks

LIFE-CYCLE STAGE	PLASTIC FUEL TANK	STEEL FUEL TANK
Material Consumption	• Assume that HDPE is the only composition of the fuel tank • HDPE is made from crude oil • HDPE processing is nonreversible • The oil deposit on earth is plenty • HDPE production needs 80.98 (MJ/kg) [45] • Emissions are not significant	• Assume that Carbon Steel is the only composition of the fuel tank • Carbon steel processing is reversible • The iron ore deposit is plenty • Carbon steel production is estimated of 33.5 (MJ/kg) • Emissions are significant
Mfg.	• More efficient process of fuel sender unit assembly • Molded-in color in black • Some chemical additive needed, such as adhesives • Overall scrap rate is 1.7% [45] • Production energy is 13.96 (MJ/kg) [45] • Emissions are not significant	• More energy consumed for fuel sender unit assembly • Additives have no negative effects on material recycling • Overall scrap rate is 18.9% [45] • Production energy is 2.658 (MJ/kg) [45] • Some heavy metal residuals will be released during the processes
Use	• Thicker walls and bigger • Efficient space utilization • Easier maintenance • Lighter weight and less fuel consumption • Safer and less evaporative emissions	• Thinner wall • Stamping and welding limit the flexible design • Heavier • Coating is necessary for corrosion prevention • Metal fatigue may happen
End-of-life management	• Reuse is possible • Landfilled after shredding • Assume the shredding efforts are same as steel fuel tanks	• Reuse is impossible • 100% material recycling • Emissions are significant

Table 4-2 Modified HOQ of raw material consumption stage

Material consumption	Importance rating	Plastic fuel tank	Steel fuel tank
Deposit on earth	0.074	[0,1,2]	[0,1,2]
Renewable resource	0.223	[0,1,2]	[0,1,2]
Efficient material processing	0.54	[1,3,5]	[8,9,10]
Less Air emissions	0.1	[1,3,5]	[0,1,2]
Less Solid waste	0.037	[8,9,10]	[0,1,2]
Less Water effluents	0.027	[0,1,2]	[1,3,5]
	Absolute score	[0.94, 2.58, 4.22]	[4.35, 5.38, 6.4]

Table 4-3 Modified HOQ of manufacture & assembly stage

Manufacture	Importance rating	Plastic fuel tank	Steel fuel tank
Modular design	0.057	[0,1,2]	[0,1,2]
Ease of handling	0.057	[1,3,5]	[0,1,2]
Components assembly	0.086	[1,3,5]	[0,1,2]
Assemble onto vehicle	0.043	[1,3,5]	[1,3,5]
Less scrap rate	0.275	[8,9,10]	[0,1,2]
Molded-in color	0.03	[8,9,10]	[0.0.0]
Min. material variety	0.118	[0,1,2]	[1,3,5]
Economy production energy	0.267	[0,1,2]	[1,3,5]
Emissions	0.267	[8,9,10]	[0,1,2]
	Absolute score	[4.76, 6.15, 7.53]	[0.43, 2.03, 3.62]

Table 4-4 Modified HOQ of use & distribution stage

Manufacture	Importance rating	Plastic fuel tank	Steel fuel tank
Fuel carry capacity	0.085	[1,3,5]	[0,1,2]
Thicker wall	0.171	[8,9,10]	[1,3,5]
Ease of replacing fuel sender	0.058	[1,3,5]	[0,1,2]
Less coating	0.293	[8,9,10]	[0,0,0]
Less fatigue	0.147	[8,9,10]	[0,1,2]
Fuel economy	0.091	[1,3,5]	[0,1,2]
Evaporative and emissions	0.156	[1,3,5]	[0,1,2]
	Absolute score	[5.28, 6.67, 8.06]	[0.17, 1.05, 1.93]

Table 4-5 Modified HOQ of end-of-life management stage

Manufacture	Importance rating	Plastic fuel tank	Steel fuel tank
Standardization	0.059	[1,3,5]	[1,3,5]
Ease of dismantling	0.106	[1,3,5]	[1,3,5]
Recyclable	0.287	[0,0,0]	[8,9,10]
Reusable	0.144	[1,3,5]	[0,0,0]
Economy shredding process	0.243	[0,1,2]	[0,1,2]
Landfill	0.121	[0,1,2]	[8,9,10]
Emissions	0.04	[1,3,5]	[0,1,2]
	Absolute score	[1.25, 2.31, 3.37]	[4.33, 5.35, 6.37]

4.6 Overall Assessment of Fuel Tank Analysis

In this section, the AHP method will be applied again for capturing the priority weights with respect to life-cycle stages. The priority weights will then be used for calculating the overall scores. In order to facilitate interpreting the fuzzified results, defuzzification will be conducted.

To capture the priority weights of life-cycle stages with respect to the overall goal of green product design, a pairwise comparison matrix will have to be constructed as in the following matrix. The calculated results are also shown at the bottom of the following matrix.

Goal: Green product design	Raw material consumption	Manufacture & assembly	Use & distribution	End-of-life management
Raw material consumption	–	1/4	2	1/2
Manufacture & assembly	4	–	5	2
Use & distribution	1/2	1/5	–	1/3
End-of-life management	2	1/2	3	–
Priority weights	0.143	0.507	0.086	0.264
Note: I.R.=0.01				

As a result, the absolute scores may be calculated by using equation (3.7), which are:

$$OS_{\text{plastic fuel tank}} = \sum_{i=1}^{4} AS_{ij} \times W_i$$

$$= [0.94, 2.58, 4.22]*0.143 + [4.76, 6.15, 7.53]*0.507+$$

$$[5.28, 6.67, 8.06]*0.086 + [1.25, 2.31, 3.37]*0.264$$

$$= [3.33, 4.67, 6.00]$$

and

$$OS_{\text{steel fuel tank}} = \sum_{i=1}^{4} AS_{ij} \times W_i$$

$$= [4.35, 5.38, 6.40]*0.143 + [0.43, 2.03, 3.62]*0.507 +$$

$$[0.17, 1.05, 1.93]*0.086 + [4.33, 5.35, 6.37]*0.264$$

$$= [2.00, 3.30, 4.60]$$

For defuzzifying the overall scores, the membership functions will have to be generated along with the overall scores. With respect to the plastic fuel tank, the membership function is:

$$\mu_{\text{plastic fuel tank}} = \begin{cases} 0 & x \le 3.33 \\ \dfrac{x-3.33}{1.34} & 3.33 \le x \le 4.67 \\ \dfrac{6-x}{1.33} & 4.67 \le x \le 6 \\ 0 & x \ge 6 \end{cases}$$

And, the membership function of steel fuel tank may be obtained as:

$$\mu_{\text{steel fuel tank}} = \begin{cases} 0 & x \le 2 \\ \dfrac{x-2}{1.3} & 2 \le x \le 3.3 \\ \dfrac{4.6-x}{1.3} & 3.3 \le x \le 4.6 \\ 0 & x \ge 4.6 \end{cases}$$

Using equation (3.8), the defuzzified overall scores may be obtained. The defuzzified overall score of the plastic fuel tank is approximately equal to 4.67, while the steel fuel tank is equal to 3.33.

Accordingly, the results denote that the plastic fuel tank is a better design alternative in terms of the entire fuel tank's life cycle. However, the steel fuel tank still deserves some credits. For example, according to the results of individual modified HOQ analysis, the steel fuel tank has a better performance in terms of the raw material consumption and end-of-life management stages. It may also provide us an answer to why the steel fuel tank still has about a 65% market share in North America currently.

Chapter 5 Case Study of Fastener Selection

5.1 Introduction

The case of remanufacturing a four-cylinder internal combustion engine reveals the importance of fastener selection in product end-of-life management. According to German research results, it has been shown that about 32.5% of all activities in the engine disassembly process consist of loosening screws. These activities consume 54% of the entire disassembly process time [80]. It is obvious from such studies that the major part of disassembly efforts is associated with detaching fasteners.

As early as 1991, Babyak [7] mentioned that innovations in reducing both parts and fasteners might result in not only minimizing the assembly labor and the associated costs, but achieving economic product recycling as well. On the other hand, eliminating all the fasteners is most likely impossible because of the limitations of technology and/or the constraint of material strength. Therefore, implementation of product design, especially in considerations of manufacturing and end-of-life management stages, should be focused on either innovation of joining design or careful selection of joining method. In the VDI-2243 [80], a German recycling guideline, a table for selecting fastening mechanisms (snaps, bolts, etc.) based on a number of attributes including tensile strength, fatigue strength, joining expenditure, detaching expenditure and destruction expenditure is provided (Table 5-1). However, the fastener selection table in VDI 2243 is only a kind of expertise. There is no clue provided why and how the relationships between attributes of connection and joining methods can be obtained.

Table 5-1 Fastener selection table (Adapted from VDI 2243)

		Material connection		Frictional connection					Positive connection					
Characteristics of connection	Principle of connection	Adhesive bonding	Welding	Magnetic connection	Velcro fastener	Bolt/nut	Plastic bolt/nut	Spring connection	Snap joint	Bent lever connection	¼ turn fastener	Press-turn fastener	Press-press fastener	Band with lock
Carrying capacity	Static strength	⊙	●	⊙	○	●	⊙	⊙	●	●	●	⊙	⊙	●
	Fatigue strength	⊙	●	⊙	○	●	⊙	○	⊙	⊙	⊙	⊙	○	⊙
Joining behavior	Joining expenditure	⊙	⊙	●	●	⊙	⊙	●	●	●	●	●	●	●
	Guidance expenditure	○	○	⊙	●	⊙	⊙	●	●	⊙	●	●	●	⊙
Detaching behavior	Detaching expenditure	○	○	●	●	⊙	⊙	●	○	●	●	●	●	⊙
	Destruction expenditure	⊙	⊙			⊙	●		●	⊙	⊙	⊙	⊙	●
Recyclability	Product recycling	○	○	⊙	⊙	⊙	●	●	○	●	●	●	●	●
	Material recycling	⊙	●	⊙	⊙	⊙	●	●	●	●	●	⊙	⊙	●

● Good ⊙ Average ○ Bad

Even though the fastener selection table in VDI 2243 does not provide a detailed explanation, it has doubtlessly aroused researchers' attention. For instance, VerGow [81] proposed a decision support system to evaluate the selection of fasteners in the context of product recycling, material recycling, and technical aspects as illustrated in the VDI 2243.

The well-developed principles of Design for Manufacturing (DFM) and Design for Assembly (DFA) have led manufacturers to look for ways to design snap fits and quick-operating fasteners, and most importantly, eliminate mechanical fasteners. However, the growing interests in Design for Environment and "green" product design have spurred designers to reconsider the relative criteria of fastener selection. For instance, contrary to DFM and DFA, Design for Disassembly would favor threaded mechanical fasteners as a joining technique.

The numerous design principles, such as Design for Manufacturing/Assembly, Design for Serviceability/Maintainability, and Design for Disassembly, etc., have presented designers with a complex trade-off situation. In addition to considering traditional mechanical properties including tensile loading, shear loading, fatigue loading, and vibration, etc., the efficiency of detachment, break point design, and accessibility will also have to be taken into consideration.

The proposed green product design framework is designed to resolve complicated trade-off problems. Particularly, it involves a systematic method to consolidate the results from each individual analysis of life cycle stages. Hence, the proposed framework is selected to perform the evaluation of alternative joining methods. It aims at making a better choice on joining method selection so that the designed product will satisfy engineering constraints as well as environmental requirements.

The study of fastener selection starts at defining the system boundary and related assumptions, which is addressed in section 5.2. In section 5.3, the step-by-step analysis is implemented by employing the proposed framework. Some important environmentally conscious requirements related to fastener selection are illustrated, and a description of characteristics for each joining method is provided in this section.

5.2 Assumptions and System Boundary

The objective of this study is to provide a preference list among alternative joining methods. The choice of fasteners is essentially dependent upon functional requirements and cost factors. In addition to traditional considerations of functional requirements, such as engineering strengths, dimensions and tolerances, etc., environmental factors have been drawn into the scope. Basically, all joining methods provide a common function of uniting two or more materials/parts and making them permanently or semi-permanently stick together. Considering product life cycle design principles, design features, including fasteners, should be selected by analyzing their entire life-span performance. In other words, the selected feature should have maximized profits in terms of complying with material use constraints, eliminating environmental impact, and ease of assembly, maintenance and recycling.

According to the proposed green product design framework described in chapter 3, product life-cycle analysis is performed in four independent stages, which are raw material consumption, manufacture and assembly, use and distribution, and end-of-life management. In this particular study of fastener selection, the ultimate goal is to design an environmentally friendly product by means of utilizing the least cost fasteners which are produced by environmentally harmless materials, reducing the fastening efforts, and maximizing the salvage values from retired products.

In this study of fastener selection, the raw material consumption stage includes evaluating effects of the material/energy consumption and generated residue resulting from producing fasteners themselves. Since the cost of producing the fastener itself is considerably minor compared with the cost of producing and assembling parts/materials, the assumption made for this study is that all the evaluated fastening alternatives have the same production cost including all direct and indirect costs. As a result, all the alternative fastening methods will have the same contribution/effect on the raw material consumption stage. In other words, the analysis of the raw material consumption stage can be omitted in this particular study. Figure 5-1 indicates the system boundaries and the established targets for each life-cycle stage.

Life cycle stages	Target	Remark
Raw material consumption	• Less cost of fastener production • Environmental constraint on material use for producing fasteners	• Assume that all fasteners have same production cost and no violation of environmental constraints • No analysis needed
Manufacture & assembly	• Ease of assembly	• Analysis required
Use & distribution	• Ease of maintenance • Lighter weight	• Analysis required
End-of-life management	• Ease of disassembly • Ease of recycling	• Analysis required

Figure 5-1 System boundaries and targets

The analysis objects are those commonly used joining alternatives, which have seven joining methods selected from the classification of joining options (Figure 3-3). Table 5-2 shows the seven selected joining alternatives sorted by joining techniques and associated categories.

Table 5-2 Alternatives of joining method

Connection technique	Category	Alternative
Joining	Welding	1. Arc welding 2. Soldering & brazing 3. Resistance welding
	Chemical bonding	4. Adhesives
Mechanical fastening	Threaded fastener	5. Bolt and Screw
	Non-threaded fastener	6. Rivet
	Quick-operating fastener	7. Snap fit

In general, five categories that include welding, chemical bonding, threaded fastener, non-threaded fastener, and quick-operating fastener may be identified from the varied joining techniques. Welding is the process of bringing two or more materials together through the application of heat and/or pressure to produce atomic or molecular bonds across the interface. Chemical bonding is generated by adhesives which are capable of holding materials together by surface attachment. The other three joining categories, threaded fastener, non-threaded fastener, and quick-operating fastener, utilize mechanical fastening which is the attachment of components in an assembly by the tightness of fit or by the interlocking of the assembled parts themselves. The holding force is formed through an integral design feature of the components or through the use of fasteners.

5.3 Analysis and Implementation

According to the assumption in the previous section, the proposed green product design framework may be simplified from five steps to four steps, which include (1) analysis of manufacture and assembly, (2) analysis of product use and distribution, (3) analysis of end-of-life management, and (4) overall assessment. The first three steps of analysis are individual analyses whose activities involve generating product design criteria/requirements, assigning rational importance ratings to every product design criterion/requirement, determining the relationships between product design criteria/requirements and alternative joining methods, and calculating the absolute scores. The overall assessment will synthesize the results from the previous three analyses and provide a recommended preference list for selecting a joining method from a defined domain.

5.3.1 Step I – Analysis of Manufacture and Assembly

In the stage of manufacture and assembly, parts/assemblies will be assembled into ready to sell products. Fasteners play a very important role in this stage, since they will directly affect the production cost and quality of finished products. Theoretically, all product designs aim at low production costs, while keeping an acceptable quality level. Hence, this step of analysis attempts to evaluate the contribution of every joining method on facilitating the assembly process and ensuring binding quality.

The process of implementing this step analysis will start with collecting the associated environmentally conscious requirements/criteria. According to the proposed worksheet presented in Figure 3-2, the related design requirements/criteria in this step analysis may be categorized as follows.

<u>Structure</u>

(a) Ease of handling – For both manual and automatic assembly, a part with symmetrical structure will be easy to handle and orient. The selected fasteners with a symmetrical structure would be better, so as to reduce handling costs and quality risks.

(b) Design for commonality – Standard parts (part compliance) would allow one part to move so that it can mate with another. From a design for commonality standpoint, product design should avoid using specially designed fasteners, but standardized fasteners instead.

(c) Ease of access to fastening points – The assembly operations should be designed to have a "clear view". Fastening operations that require tactile sensing should be avoided.

<u>Connection</u>

(d) Minimum of number of types of fastener – From both manual and automatic assembly standpoints, tooling and fixture costs will be in proportion to the number of types of fastener.

(e) Minimum of number of joining elements – Fasteners are a major barrier to efficient assembly. Multiple joining elements mean complicated assembly motions and longer assembly times. Product design should have minimized joining elements as long as safety concerns have been fulfilled.

(f) Static strength – The capability of static strength is one of major constraints of fastener selection. In most cases, static strength includes considerations of tensile and shear stress. For a small group of joining methods, impact and peel stress will have significant influences and have to be taken into consideration.

Material

(g) Use of recycled materials – Using as much recycled material as possible for producing products and fasteners may enhance both "closed loop" and "open loop" recycling.

(h) Avoidance of using toxic materials – Hazardous/toxic materials sometimes could be applied in additives such as colorants, fillers and reinforcement materials. These vital materials will result in environmental and health problems and are usually regulated by environmental laws.

Energy

(i) Standard process – Standard assembly processes will enhance the reduction of set up and tooling costs.

(j) Ease of insertion – The capability of easy insertion of fasteners means energy saving during assembly and reassembly processes.

(k) Use of high-throughput processes – Basically, the environmental burden per unit assembled depends on through-put time, since the total environmental effects that include energy consumption and pollution generation, etc. are proportional to the time spent on the process.

On the basis of the above description of design requirements, a pairwise comparison is performed as in Figure 5-2. There are five matrices involved in Figure 5-2. The first matrix performs the comparison of categories with respect to the life cycle stage of manufacture and assembly, and the rest of the matrices conduct the comparison of criteria with respect to each category.

Based on these pairwise comparison matrices, the importance ratings for the design requirements can be calculated by using equation (3.1). The tree diagram (Figure 5-3) shows the results from the pairwise comparison matrices and the calculated importance ratings.

Once design requirements and their importance ratings have been determined, the next step of analysis is to explore the relationships between design requirements and fastening alternatives. A brief description of every alternative of joining method is provided below so that the strength of relationships can be assigned accordingly. Basically, the examined properties of joining methods consist of materials, assembly/disassembly efficiency, engineering factors, environment factors, and special requirements.

There are three most frequently adopted welding alternatives, which are arc welding, soldering/brazing, and resistance welding. The advantages and disadvantages [15][53][57] applied for welding alternatives in the assembly and manufacture stage are summarized in Figure 5-4.

Manufacture & Assembly Stage	Structure	Connection	Material	Energy
Structure	–	1/3	1	1/5
Connection	3	–	3	1
Material	1	1/3	–	1/3
Energy	5	1	3	–

Structure	(a)	(b)	(c)
(a)	-	1/2	1/2
(b)	2	-	2
(c)	2	1/2	-

Connection	(d)	(e)	(f)
(d)	-	1/2	1/2
(e)	2	-	1
(f)	2	1	-

Material	(g)	(h)
(g)	-	1/4
(h)	4	-

Energy	(i)	(j)	(k)
(i)	-	2	1/2
(j)	1/2	-	1/2
(k)	2	2	-

Figure 5-2 Pairwise comparison of manufacture & assembly stage for fastener selection

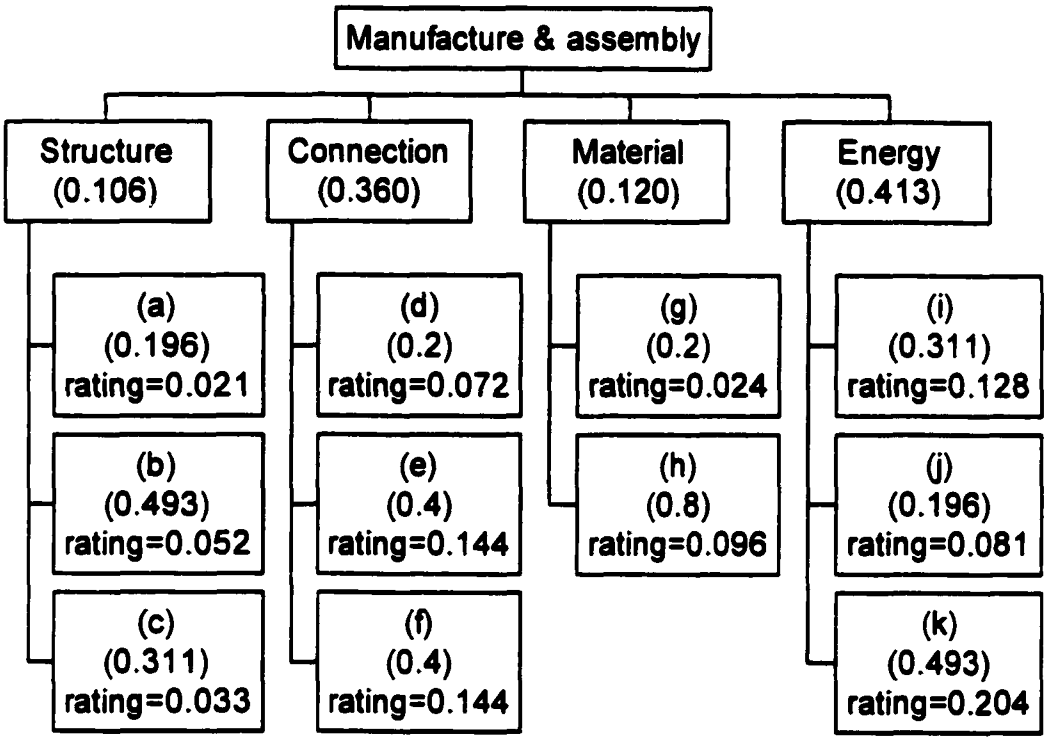


Figure 5-3 Importance ratings in the manufacture & assembly stage

	Advantages	Disadvantages
Welding in common	♦ structural integrity ♦ Wide variety of processes ♦ Wide variety of weldable base materials	♦ Unbalanced heat input leads to distortion or residual stresses ♦ Skilled operators required
Arc welding	▪ Can be highly portable ▪ Allows of joining all sizes and shapes of joints	▪ Heat of welding degrades base properties ▪ Expensive for thick sections; stringent quality requirements ▪ Welded joint may be contaminated
Soldering and brazing	▪ No significant change of base material ▪ Capability of joining dissimilar materials ▪ Easy to automate ▪ Allows joining of thin-to-thin or thin-to-thick joints	▪ Strength is very limited ▪ Requires joint edges cleaning ▪ Requires fluxing control ▪ Flux residue removal ▪ Joint gaps or clearance control (e.g. fixture required)
Resistance welding	▪ High speed of operation ▪ Minor surface preparation ▪ No filler metal consumed ▪ Less machining operation (i.e. drilling, punching) ▪ Uniform results in mass-production	▪ Capital equipment can be expensive ▪ Fixtures can be costly ▪ There is a limitation of joined materials ▪ There is a limitation on part size

Figure 5-4 Advantages and disadvantages of welding in Step I

One of the most significant advantages of welding is that welding provides structural integrity so that the welded parts may be easily handled. Welding can be applied in a wide range, since the weldable base materials cover almost all metals and many polymers, glasses, ceramics, and many composites. Welding may also meet most of the requirements of engineering strengths. The engineering strengths of welded joints may usually meet or even exceed the strength of the base material. However, heat input during welding processes may not be distributed evenly. It may result in distortion of base materials or generation of residual stresses. In order to ensure the quality of welding, well-trained operators are needed.

Arc welding has almost no limitation of size or shape of assembly. Components with complex structures may be easily arc-welded. The strength of the weld may usually achieve at least 80 percent of the base material. On the other hand, the arc welded base materials may be contaminated with electrodes during the welding processes. Arc welding can be expensive, especially for thick sections and because of stringent quality requirements.

Soldering and brazing are similar processes in which filler metal is used to join two metal parts. The melting temperatures of the fillers may distinguish soldering from brazing as well as from arc welding. Figure 5-5 shows the three basic alternatives of welding process that are based on the temperature required for the process. The solder fillers usually have a melting temperature below 450°C, while brazing fillers are primarily melted above this temperature. Soldering and brazing may be applied when dissimilar metals, electronic assemblies, and complex hollow shape assemblies are involved. On the other hand, soldering and brazing have limited engineering strength and some special treatments have to be made for cleaning the surfaces of joints.

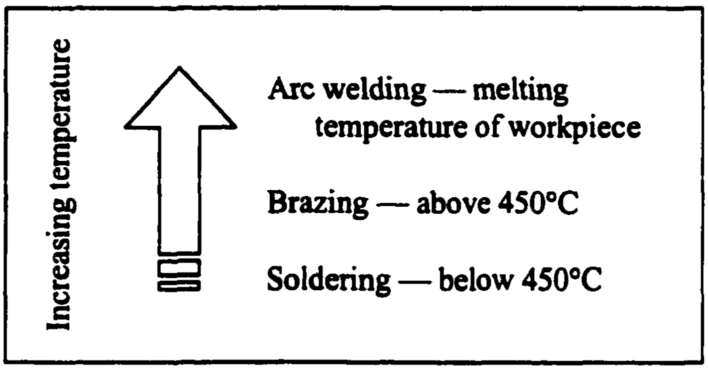


Figure 5-5 Alternatives of welding processes

Spot welding is one example of resistance welding. It is performed with high electric currents and low potential passing through workpieces between electrodes. Unlike other welding methods, resistance welding doesn't need special surface preparation and filler metal. Compared with threaded and non-threaded fasteners, resistance welding requires no drilling and punching for assembly processes. Therefore, resistance welding may have higher production rates.

Adhesive joints are often less costly and more easily produced. They are suitable for joining porous, fragile, or heat-sensitive materials. Other applications of using adhesive bonding are when materials of dissimilar composition, thickness, or modulus must be joined together. Even though adhesively bonded joints can be engineered for high strength, adhesive bonding is not good in extreme cases of strength requirements and temperature variations. Some advantages and disadvantages of adhesive bonding

[15][53][57] associated with life cycle stage of assembly and manufacture are summarized in Figure 5-6.

Advantages	Disadvantages
• Capability of high load-carrying • Stress concentrations are minimized • Allows diverse size or shape of assembled objects to be bonded • Cost reduction • Good at joining dissimilar materials • Ease of assembly	• Requires surface preparation • Solvents used may be harmful to workers • Special control may be needed for shelf inventory • Long cure times may be required • Inspection may be difficult • Fixturing cost may be significant

Figure 5-6 Advantages and disadvantages of adhesive bonding in Step I

A typical example of threaded fastener is bolt and screw. Bolts usually develop the clamping force by assembling a nut on an externally threaded shank. The nuts may not be necessary in some cases if the joint element provides internal threads. Screws generally have the same specifications as bolts, but they are usually limited to smaller diameters.

Bolts and screws are available in varied sizes and materials, so they can be seen in a wide range of applications. For ease of manufacture and assembly, bolts and screws excel in joining the same or dissimilar materials with few size or shape limitations. However, the assembly labor costs may be high. Figure 5-7 lists some criteria for this step of analysis, which are primarily the advantages and disadvantages of threaded fasteners.

Advantage	Disadvantage
• Capable of joining dissimilar materials • Ease of automation • No change to the chemical composition or microstructure of the materials composing the parts being joined • Provides damage tolerance to assembly	• Creates significant stress concentration at the point of fastening • Installation labor is high • Time consuming processes • May require multiple fastening points to balance the clamping force

Figure 5-7 Advantages and disadvantages of threaded fasteners in Step I

Because of their simplicity, rivets are one of the most frequently used unthreaded fasteners. The major benefits of using rivets are that they produce permanent joints, and are less expensive on a per fastener basis than threaded fasteners. However, the engineering strengths of rivets (e.g. shear and tension) are usually low. Thus, the number of rivets required in a specific joint may be increased. Therefore, the total cost of a joint has to be carefully evaluated when seeking an economical production plan. A summary of advantages and disadvantages of rivets in this step of analysis is provided in Figure 5-8.

A number of fastener types, such as snap fits, lever-actuated, turn-operated, slide-action etc., can be categorized as quick-operating fasteners. Snap fits have been selected as one of the analysis objects, since they have been playing an important role among varied quick-operating fasteners in modern manufacturing. The rising trend of using engineered polymers leads designers to pay more attention to innovation of snap fits. Polymers and some easily deformed materials can only allow a low insertion force to avoid deforming. Snap fits and their design features can not only keep the insertion force low, but also provide a simple installation operation. Therefore, snap fits are now widely applied for product design in order to enhance assembly. Figure 5-8 shows the advantages and disadvantages of snap fits in this step analysis.

Advantage	Disadvantage
• Provides a permanent joint • Ease of quality inspection • Low cost on a per fastener basis • Allows joining of dissimilar materials • Riveting processes can be done before the components are cleaned, or after final painting or other finishing.	• Static strengths, such as shear and tension, are lower than bolt and screw • Requires a greater number of rivets in one joint • Requires greater clearance around rivet locations • Requires accurate hole diameters

Figure 5-8 Advantages and disadvantages of rivets in Step I

Advantage	Disadvantage
• Requires low insertion force with high pull-out resistance • Provides a low-cost method for fastening parts together • Ease of automatic assembly • Suitable with many different materials	• Requires precise dimensional control of the mating parts • Low static strengths • No standard specifications

Figure 5-9 Advantages and disadvantages of snap fits in Step I

The above identified advantages and disadvantages for each alternative joining method in the life cycle stage of manufacture and assembly are qualitative descriptions. The next step is to translate the qualitative descriptions into quantitative analysis. The translation will be accomplished by using the proposed methodology of modified HOQ, as performed in Table 5-3.

Similar to the fuel tank example, a numerical scale {0, 1, 3, 9} is selected to define relationships in this case study of fastener selection. The linguistic meanings of the scale imply that "0" has no relation at all, "1" has a weak relationship, "3" has a moderate relationship and "9" has a very important relationship. After converting the selected numerical scale to fuzzy numbers, in terms of fuzzy number expression (as described in section 3.2.5.2), the selected scale may be recorded as {[0, 0, 0], [0, 1, 2], [1, 3, 5], [8. 9. 10]}. The symbol "—" is used to represent the scale of [0, 0, 0] in the following modified HOQ practices. For instance, welding and adhesive bonding have the advantage of maintaining structural integrity, so they may enhance the design criteria of ease of handling. In other words, welding and adhesive bonding are strongly related to the design criteria of ease of handling. On the other hand, joints that utilize bolt and snap fit as joining techniques have difficulty maintaining structural integrity, so they are weakly related to the design criteria of ease of handling. The rest of the assigned relationships and calculated absolute scores for the manufacture and assembly stage are addressed in Table 5-3.

Table 5-3 Modified HOQ of manufacture & assembly stage

Design criteria	Importance rating	Arc welding	Soldering /brazing	Resistance welding	Adhesive	Screw & bolt	Rivet	Snap fit
(a)	0.021	[8,9,10]	[8,9,10]	[8,9,10]	[8,9,10]	[0,1,2]	[1,3,5]	[0,1,2]
(b)	0.052	[0,1,2]	[0,1,2]	[0,1,2]	[0,1,2]	[8,9,10]	[8,9,10]	[1,3,5]
(c)	0.033	[0,1,2]	[0,1,2]	[1,3,5]	[1,3,5]	[1,3,5]	[8,9,10]	[8,9,10]
(d)	0.072	[0,1,2]	[0,1,2]	[0,1,2]	[1,3,5]	[1,3,5]	[8,9,10]	[8,9,10]
(e)	0.144	[0,1,2]	[0,1,2]	[0,1,2]	[0,1,2]	[8,9,10]	[1,3,5]	[1,3,5]
(f)	0.144	[8,9,10]	[8,9,10]	[8,9,10]	[1,3,5]	[8,9,10]	[1,3,5]	[1,3,5]
(g)	0.024	—	—	[8,9,10]	—	[0,1,2]	[0,1,2]	[1,3,5]
(h)	0.096	[0,1,2]	[1,3,5]	[8,9,10]	[0,1,2]	[8,9,10]	[8,9,10]	[8,9,10]
(i)	0.128	[0,1,2]	[0,1,2]	[1,3,5]	[1,3,5]	[1,3,5]	[8,9,10]	[8,9,10]
(j)	0.081	—	—	—	—	[1,3,5]	[8,9,10]	[8,9,10]
(k)	0.204	[0,1,2]	[0,1,2]	[1,3,5]	[8,9,10]	[1,3,5]	[8,9,10]	[8,9,10]
	Absolute score	[3.108, 2.214, 1.32]	[3.396, 2.406, 1.416]	[5.211, 3.928, 2.645]	[4.719, 3.448, 2.177]	[7.04, 5.523, 4.006]	[8.253, 6.945, 5.637]	[8.002, 6.639, 5.276]

5.3.2 Step II – Analysis of Product Use and Distribution

In this step, design concerns focus on product distribution, use and maintenance. This is an energy intensive stage, since it represents the majority of product life cycles. Energy consumption is, therefore, the major consideration in this step of analysis. An adopted joining method should aim at reducing energy consumption such as enhancing storage, maintenance, and reducing total weight. In addition to the consideration of energy consumption, some special concerns such as resistance in harsh environments during the product use stage and the functional requirement of sealing are all related to fastener selection.

Divided by categories of structure, connection, material and energy, some general design requirements/criteria with respect to fastener selection in the use and distribution stage may be listed as follows.

<u>Structure</u>

(a) Ease of piling or storing – The configuration of products will affect transportation, especially with respect to piling and storing. An easy pile-up product may save storage space and enhance efficient transportation.

(b) Ease of packaging – Design for ease of packaging would reduce environmental burdens and moderate resource depletion.

<u>Connection</u>

(c) Design for maintenance and replacement – The objective of maintenance is to assure the product an error-free performance throughout its useful life cycle. Standardization and interchangeability are two major factors to achieve maintainability. These two factors also offer an index for fastener selection.

(d) Useful life prolongation (e.g. reliable joint) – Heuristically, the longer the product lasts, the less the material consumed and waste generated. A reliable fastener used would ensure longer product life.

(e) Fatigue strength – The nature of fatigue is such that failure occurs at a certain static strength level that is usually lower than the rated static strength. Fatigue happens due to repetitive or dynamic loading. Hence, joint design must consider the factors of stress concentrations and fatigue life.

Material

(f) Wear and tear prevention – Wear and tear will increase the difficulty of recycling. Components should use either wear preventive or easy detect materials, so that the recycling strategy could be easily determined after their useful life.

(g) Use of rust proof joints in accordance with harsh environment – Rusted-joining elements would increase the uncertainty of disassembly processes. Hence, use of rust proof joints should be considered if the product will be exposed to a harsh environment during the use stage.

Energy

(h) Design for low volume weight – It is always true that low product weight will decrease the energy consumption during the product useful life and the transportation cost between manufacturing facilities and customers.

(i) Seal and insulation fulfillment – If some energy saving functions are needed (e.g., seal and insulation), fasteners would be the key elements to fulfill the requirements.

According to the above description of design requirements in the use and distribution stage, a pairwise comparison is performed as in Figure 5-10. The individual results of pairwise comparison matrices and importance ratings of design criteria are summarized in Figure 5-11.

In order to determine the relationships between design requirements/criteria and alternatives of joining method, the performance characteristics of each joining alternative in the product use and distribution stage have to be explored. These performance characteristics in terms of advantages and disadvantages [69] are more or less related to the selected design requirements/criteria and are tabulated in the following three figures (from Figure 5-12 to Figure 5-14).

Use and distribution	Structure	Connection	Material	Energy
Structure	–	1/5	1/4	1/4
Connection	5	–	2	1
Material	4	1/2	–	1
Energy	4	1		–

Structure	(a)	(b)
(a)	–	1
(b)	1	–

Connection	(c)	(d)	(e)
(c)	–	2	1
(d)	1/2	–	1/3
(e)	1	3	–

Material	(f)	(g)
(f)	–	1/2
(g)	2	–

Energy	(h)	(i)
(h)	–	2
(i)	1/2	–

Figure 5-10 Pairwise comparison of use and distribution stage for fastener selection

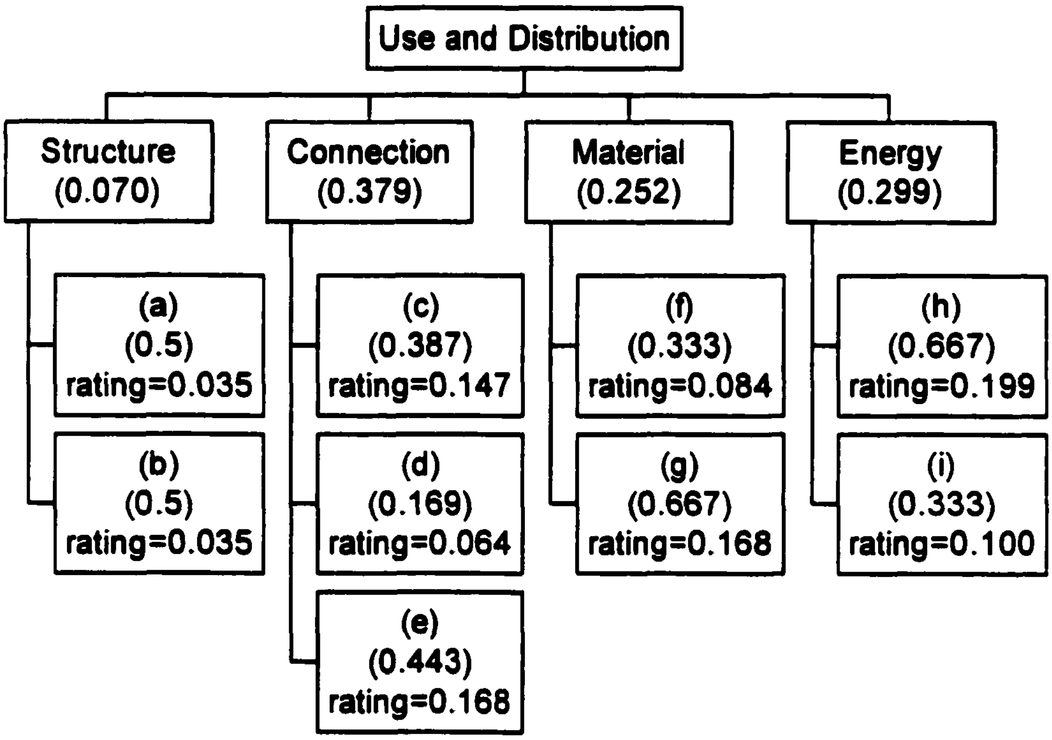


Figure 5-11 Importance ratings in use and distribution stage

	Advantages	Disadvantages
Welding in common	◆ Precludes joint loosening ◆ Produces light weight assemblies ◆ Offers leak-tight joints ◆ Prevents wear and tear	◆ Product maintenance is difficult
Arc welding	▪ Offers neat appearance	▪ Corrosion may be significant
Soldering and brazing	▪ Offers neat appearance ▪ Allows electrical conductivity ▪ Offers corrosion resistance	▪ Limited elevated temperature service and stability
Resistance welding	▪ Offers corrosion resistance	▪ Smooth contours may be compromised with joint design

Figure 5-12 Advantages and disadvantages of welding in Step II

Advantages	Disadvantages
• Resists galvanic corrosion • Produces assemblies in light weight • Provides sound deadening • Provides mechanical damping • Offers electrical insulation • Insulates heat transfer • Resists fatigue or cyclic loads • Provides joints with smooth contours	• Limits on extreme strength requirement • Limits on broad temperature variations • Joint repair and life prolonging are difficult • There is an upper service temperature • Natural adhesives are subject to attack by bacteria, mold, rodents, and vermin • There are many environmental concerns (e.g. light, oxidation, moisture, salt spray, biological factors

Figure 5-13 Advantages and disadvantages of adhesive bonding in Step II

	Advantages	Disadvantages
Bolt and screw	◆ Essential for the purposes of repair of damage, access for maintenance or servicing, modification, and expansion ◆ Allows relative motion between parts	◆ Stress concentration at the point of fastening ◆ There can be a weight penalty compared to other joining methods ◆ Joints can loosen in service as a result of vibration ◆ May permit moisture, water, or fluid intrusion ◆ Corrosion effects may be significant
Rivet	• Allows relative rotation between parts • Provides attractive appearance	• High enough tensile loads can pull out the clinch • Not easy for maintenance • Vibrations may loosen the joint • May permit moisture, water, or fluid intrusion • Corrosion effects may be significant
Snap fits	▪ Allows stress relaxation after being assembled ▪ Resistant to loosening by vibration ▪ Allows relative motion between parts	▪ May permit moisture, water, or fluid intrusion

Figure 5-14 Advantages and disadvantages of mechanical fasteners in Step II

On the basis of advantages and disadvantages of alternative joining methods described above, the modified house of quality for the use and distribution stage may be performed as in Table 5-4.

Table 5-4 Modified HOQ of use and distribution stage

Design criteria	Importance rating	**Arc welding**	**Soldering /brazing**	**Resistance welding**	**Adhesive**	**Screw & bolt**	**Rivet**	**Snap fit**
(a)	0.035	[8,9,10]	[8,9,10]	[1,3,5]	[8,9,10]	[0,1,2]	[1,3,5]	[0,1,2]
(b)	0.035	[8,9,10]	[8,9,10]	[1,3,5]	[8,9,10]	[1,3,5]	[8,9,10]	[1,3,5]
(c)	0.147	[0,1,2]	[0,1,2]	[0,1,2]	[0,1,2]	[8,9,10]	[1,3,5]	[1,3,5]
(d)	0.064	[8,9,10]	[8,9,10]	[8,9,10]	[0,1,2]	[1,3,5]	[1,3,5]	[1,3,5]
(e)	0.168	[8,9,10]	[8,9,10]	[8,9,10]	[1,3,5]	[1,3,5]	[1,3,5]	[1,3,5]
(f)	0.084	[8,9,10]	[8,9,10]	[8,9,10]	[8,9,10]	[1,3,5]	[1,3,5]	[1,3,5]
(g)	0.168	[1,3,5]	[1,3,5]	[8,9,10]	[8,9,10]	[0,1,2]	[0,1,2]	[1,3,5]
(h)	0.199	[8,9,10]	[8,9,10]	[8,9,10]	[8,9,10]	[0,1,2]	[0,1,2]	[1,3,5]
(i)	0.1	[8,9,10]	[8,9,10]	[8,9,10]	[1,3,5]	[0,1,2]	[0,1,2]	[0,1,2]
	Absolute score	[7.984, 6.816, 5.648]	[7.984, 6.816, 5.648]	[8.474, 7.404, 6.334]	[6.972, 5.704, 4.436]	[4.229, 2.878, 1.527]	[3.774, 2.276, 0.778]	[3.595, 2.73, 0.865]

5.3.3 Step III – Analysis of End-of-life Management

The strategies for product end-of-life management are known as product/part reuse, remanufacturing, and material recycling. The fastener selection in this step attempts to fulfill these strategies. Both detachable joining elements and easy break fasteners would favor the implementation of strategies in the end-of-life management stage. Use of compatible materials is another important issue that would make material recycling efficient. This step of analysis will evaluate the associated fastener selection guidelines/requirements so as to facilitate product end-of-life management.

In order to effectively and efficiently manage product retirement, many design guidelines/criteria with respect to fastener selection may be found. In accordance with the proposed worksheet (refer to Figure 3-2), the collected design requirements may be categorized as follows.

Structure

(a) Ease of innovation/expansion – It is important that product structure may enhance updating with the newest technologies. A typical example is the property of plug-and-play in personal computers, which provides computers the ability of easy expansion.

(b) Ease of access to detaching points – It includes identifying separation points and providing enough room for disassembly operations. These efforts will make disconnecting operations simple and fast.

Connection

(c) Use of common tools for disassembly – Connecting elements that can be dismantled using simple tools may reduce the direct cost of end-of-life management.

(d) Use of detachable (easy disassembly) joining elements – Metal fasteners should be detached and removed in the beginning of material recycling processes, especially when they are used in plastic products. Whenever reuse/remanufacture is feasible, the desired parts would have to be disassembled from the adjacent parts.

(e) Ease of breaking for removing fasteners – Break points applied on fasteners could facilitate the disassembly process. It is the case that is often applied on snap fits. The break points can also be provided on jointed parts. For example, a molded metal insert is designed to provide a weak area that would easily break-off from the attached surfaces with limited loss of plastic materials.

(f) No damage of components while removing joining elements – Removing joint elements without damaging the fastened parts is the fundamental requirement to achieve part reuse and remanufacture.

Material

(g) Use of marking codes – Marking codes (by in-mold, bar code, or color) applied on both products and joint elements may significantly reduce time consumption of sorting materials in recycling processes.

(h) Recycling oriented design – Recycling oriented design might include enhancing recyclability and using recyclable materials. Recyclability will be enhanced if the materials are compatible for recycling together. For instance, molded-in metal reinforcements or fasteners should be eliminated, since it may render recycling uneconomical, or even impossible. The use of recyclable materials will be the fulfillment of "closed-loop" recycling processes. The joining elements should be made of recyclable materials whenever feasible.

(i) Minimum of material variety – A major obstacle of material recycling is the process of purification. The selected fasteners should either enhance the separation of varied materials or be recycling compatible with the joined parts.

(j) Avoidance of contaminants – The applied fastening techniques should avoid becoming contaminants in the recycling processes. Some adhesives are typical contaminants in the recycling processes.

Energy

(k) Generation of efficient disassembly sequences – The most valued parts should be able to be removed earlier so that recycling strategies of product reuse/remanufacture may be accomplished economically.

(l) Enable simultaneous disassembly & separation – Designers should always aim at automated disassembly operations to enable simultaneous disassembly and separation.

The importance ratings with respect to the design requirements/criteria in this step analysis can be obtained by means of conducting a pairwise comparison (Figure 5-15) among the requirements/criteria. The results of importance ratings are expressed in Figure 5-16.

The next task in this step of analysis is to discover the associated advantages and disadvantages for each alternative joining method. As described in the previous sections, the identified advantages and disadvantages (shown in Figure 5-17 to Figure 5-19) will be used as criteria to determine the relationships between design requirements/criteria and alternative joining methods.

Manufacture & Assembly Stage	Structure	Connection	Material	Energy
Structure	–	1/4	1/4	1
Connection	4	–	2	3
Material	4	1/2	–	3
Energy	1	1/3	1/3	–

Structure	(a)	(b)
(a)	-	1/5
(b)	5	-

Connection	(c)	(d)	(e)	(f)
(c)	-	1/4	1/2	1/3
(d)	4	-	2	2
(e)	2	1/2	-	1/2
(f)	3	1/2	2	-

Material	(g)	(h)	(i)	(j)
(g)	-	1/2	1/2	1/2
(h)	2	-	1	2
(i)	2	1	-	3
(j)	2	1/2	1/3	-

Energy	(k)	(l)
(k)	-	1
(l)	1	-

Figure 5-15 Pairwise comparison of end-of-life management stage for fastener selection

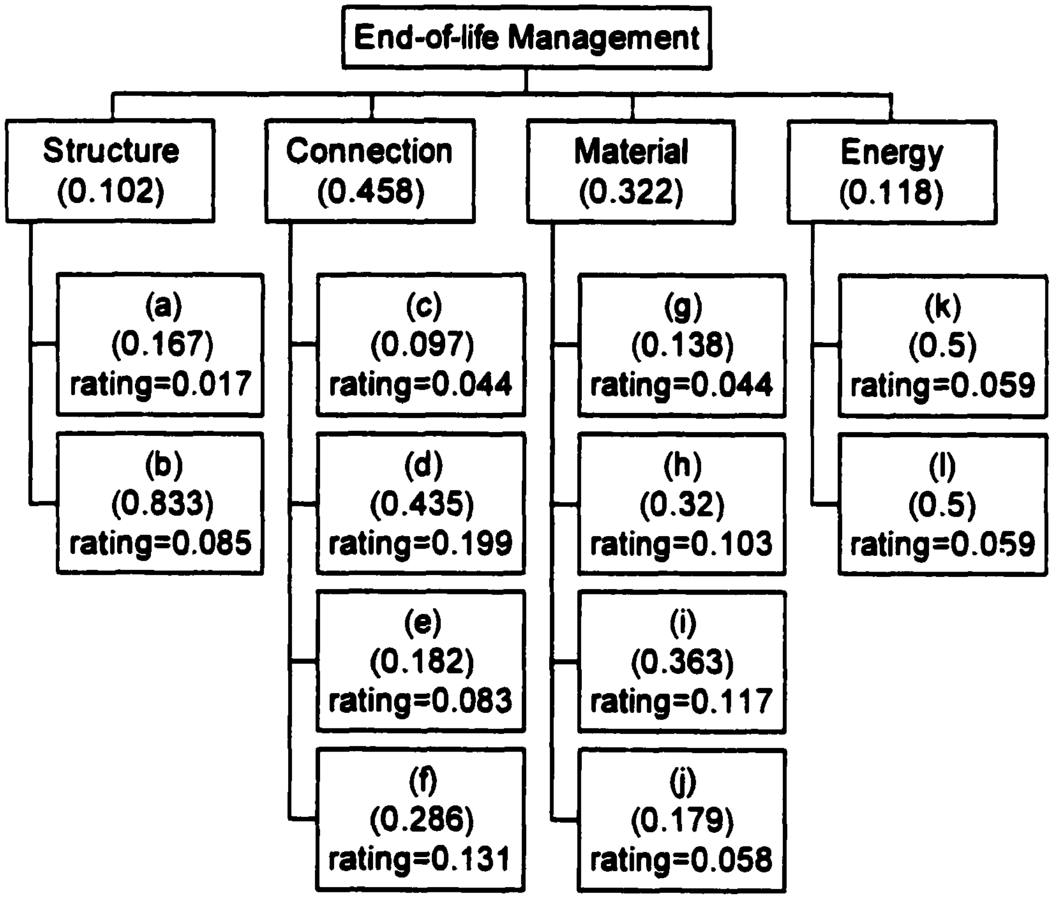


Figure 5-16 Importance ratings in end-of-life management stage

	Advantages	Disadvantages
Arc welding		◆ Prevents disassembly ◆ Contamination may occur ◆ Electrodes may not be identified
Soldering and brazing	• Capable of disassembly	• Filler metal may be the source of contamination • Filler metal is difficult to identify
Resistance welding	▪ Enhances recycling oriented design	▪ Prevents disassembly

Figure 5-17 Advantages and disadvantages of welding in Step III

Advantages	Disadvantages
• May enhance material recycling if adhesives are recyclable • May allow simultaneous disassembly if water-soluble adhesives are used	• Prevents disassembly • Solvents used for disassembly may be toxic

Figure 5-18 Advantages and disadvantages of adhesive bonding in Step III

	Advantages	Disadvantages
Bolt and screw	♦ Allows simple and practical disassembly without component damage ♦ No bonds generated, nor are contaminants used ♦ Automatic disassembly processes may be achieved ♦ Material coding may be applied	♦ Rusted joints may increase disassembly difficulty ♦ Enough clearance required for performing disassembly
Rivet	• No bonds generated, nor are contaminants used • Automatic disassembly processes may be achieved	• Not easy to disassemble • Special tools required for disassembly • Enough clearance required for performing disassembly
Snap fits	▪ No bonds generated, nor are contaminants used ▪ Allows design for easy breaking	▪ Special tools may be required for disassembly ▪ Joint may contain dissimilar materials which will prevent material recycling

Figure 5-19 Advantages and disadvantages of mechanical fasteners in Step III

On the basis of advantages and disadvantages of alternative joining methods described above, the modified house of quality for the end-of-life stage may be performed as in Table 5-5.

Table 5-5 Modified HOQ of end-of-life stage

Design criteria	Importance rating	Arc welding	Soldering /brazing	Resistance welding	Adhesive	Screw & bolt	Rivet	Snap fit
(a)	0.017	[0,1,2]	[0,1,2]	[0,1,2]	[0,1,2]	[8,9,10]	[1,3,5]	[8,9,10]
(b)	0.085	—	—	—	—	[1,3,5]	[1,3,5]	[1,3,5]
(c)	0.044	—	—	—	[0,1,2]	[8,9,10]	[1,3,5]	[1,3,5]
(d)	0.199	—	[0,1,2]	—	[0,1,2]	[8,9,10]	[1,3,5]	[1,3,5]
(e)	0.083	—	—	—	—	[0,1,2]	[1,3,5]	[8,9,10]
(f)	0.131	—	[0,1,2]	—	[0,1,2]	[8,9,10]	[1,3,5]	[8,9,10]
(g)	0.044	—	—	—	—	[1,3,5]	[0,1,2]	[0,1,2]
(h)	0.103	[8,9,10]	[8,9,10]	[8,9,10]	[1,3,5]	[1,3,5]	[1,3,5]	[0,1,2]
(i)	0.117	[0,1,2]	[0,1,2]	[8,9,10]	[0,1,2]	[1,3,5]	[0,1,2]	[0,1,2]
(j)	0.058	[0,1,2]	[0,1,2]	[8,9,10]	[0,1,2]	[1,3,5]	[8,9,10]	[8,9,10]
(k)	0.059	—	[0,1,2]	—	—	[8,9,10]	[1,3,5]	[8,9,10]
(l)	0.059	—	[0,1,2]	—	—	[8,9,10]	[8,9,10]	[1,3,5]
	Absolute score	[1.414, 1.119, 0.824]	[2.31, 1.567, 0.824]	[2.814, 2.519, 2.224]	[1.647, 0.875, 0.103]	[7.291, 5.885, 4.479]	[5.097, 3.377, 1.657]	[5.808, 4.557, 3.306]

5.3.4 Step IV – Overall Assessment

The forth step of analysis is to synthesize the previous three analyses. In this step of analysis, the AHP method would normally be employed for capturing the priority weights with respect to life-cycle stages. The priority weights for life-cycle stages are essential for determining the overall scores.

In order to capture the priority weights of life-cycle stages, a pairwise comparison matrix has to be conducted with respect to the overall goal of green product design. Since the priority weights will be product/process dependent, different products/processes may be expected to have varied results from the pairwise comparison. For example, pop cans have a short usage life, and a relatively significant recycling profit. Hence, their priority weights will be concentrated on manufacture and end-of-life stages. On the contrary, light bulbs have a low production cost, minor recycling profits, and a prolonged energy consumption life. Therefore, the use stage should receive the majority of weight in light bulbs analysis.

In this fastener selection case study, the product type is not specified. It is supposed that a product with equally important life cycle stages is under analysis. In other words, all the comparisons of life cycle stages have the same unity values (see Figure 5-20). Applying the AHP method, the priority weights for the life cycle stages, which are manufacture and assembly, use and distribution, and end-of-life management stages, are evenly distributed.

Goal: Green product design	Manufacture & assembly	Use & distribution	End-of-life management
Manufacture & assembly	–	1	1
Use & distribution	1	–	1
End-of-life management	1	1	–
Priority weights	0.333	0.333	0.333

Figure 5-20 Pairwise comparison of life cycle stages

Applying the equation (3.7), the overall scores of the alternatives of fastening mechanisms may be obtained; these are:

$$OS_{\text{Arc welding}} = \sum_{i=1}^{4} AS_{ij} \times W_i$$

$$= [3.108, 2.214, 1.32]*0.333 + [7.984, 6.816, 5.648]*0.333 +$$

$$[1.414, 1.119, 0.824]*0.333$$

$$= [4.164, 3.38, 2.595]$$

$$OS_{\text{Soldering/brazing}} = [4.559, 3.593, 2.627]$$

$$OS_{\text{Resistance welding}} = [5.494, 4.612, 3.731]$$

$$OS_{\text{Adhesive}} = [4.442, 3.339, 2.236]$$

$$OS_{\text{Screw/bolt}} = [6.18, 4.757, 3.334]$$

$$OS_{\text{Rivet}} = [5.702, 4.195, 2.688]$$

$$OS_{\text{Snap fit}} = [5.796, 4.637, 3.478]$$

The overall scores calculated above are fuzzy numbers. In order to make a comparison among these overall scores, they have to be defuzzified into crisp numbers. Applying Yager's Centroid method (e.g., equation 3.8), the results of defuzzified overall scores and the associated ranking are tabulated in Figure 5-21.

	Arc welding	Soldering /brazing	Resistance welding	Adhesive	Screw & bolt	Rivet	Snap fit
Crisp overall scores	3.38	3.59	4.61	3.34	4.76	4.20	4.64
Rank	6	5	3	7	1	4	2

Figure 5-21 Defuzzified overall scores and ranking

The ranking shown in Figure 5-21 indicates the preference order when the life cycle stages are equally important. In other words, counting on the performance in all product life-cycle stages, screw and bolt is the most preferred fastening mechanism, and adhesive bonding is the last alternative that designers should take into consideration.

Chapter 6 Conclusion and Future Work

Green product design is the current product design trend. Stringent legislation and environmental standards, and ever-growing environmental problems have motivated designers and manufacturers to explore the theories of green product design. As well, customers' awareness and worldwide competitions have also been attracting designers' and manufacturers' attention respecting innovations of the tools for green product design.

The issues of green product design may be applied to a wide range including material selection, parts design and manufacturing process improvement. The ultimate goal of green product design is to conserve nature resources, minimize depletion of non-renewable resources and use sustainable practices for managing renewable resources. The varied considerations and constraints resulting from the practice of green product design will cause designers to face complicated trade-offs. In other words, it is harder than ever for a designer to make a decision on green product design.

The proposed framework is a green product design tool. It focuses on seeking better environmental performance by means of selecting environmentally friendly design alternatives. Two parts contained in the proposed framework may facilitate the selection assignment, so as to make the framework effective. These two parts are (1) the individual assessment tool, and (2) the overall assessment method.

The individual assessment tool, namely modified HOQ, is modeled by incorporating House of Quality, Analytic Hierarchy Process and fuzzy set theory. The environmental considerations are usually spread broadly, which include environmental impact reduction throughout the product life cycle, efficiency in the use of nature resources, waste control through production processes, and end-of-life management. The HOQ provides a mechanism to map widespread environmental considerations into feasible design alternatives, so that the relationships between design alternatives and environmental requirements may be analyzed. For improving the shortcomings of HOQ, the AHP is employed to ensure obtaining rational importance weightings along with environmental requirements, and fuzzy numbers are used to substitute the imprecise artificial expressions of relationships. Consequently, the modified HOQ method has proved to be suitable for capturing environmentally conscious requirements and evaluating the potential design alternatives.

The overall assessment method in the proposed framework provides a mechanism to consolidate results obtained from the analyses of each product life cycle stage, which is performed on the proposed individual assessment tool (i.e., modified HOQ). The concept of product life-cycle design is drawn in the proposed framework by the overall assessment. Essentially, product life cycle is divided into four stages, which may be synthesized by the proposed overall assessment.

The proposed green product design framework has been illustrated by conducting a case study comparison between plastic and steel fuel tanks. In this case study, fuel tanks used for automobiles are under investigation. A qualitative description of plastic and steel fuel tanks is quantified by using the proposed green product design framework. As a result, an importance ranking of these two types of fuel tanks is provided, and the conclusion is made that plastic fuel tanks have a better environmental performance than steel fuel tanks in terms of the whole life cycle of fuel tanks. It is also proved that the proposed green product design framework is a useful tool in product design, especially in the evaluation of material selection.

The proposed green product design framework also demonstrates that it can work for fastener selection. In chapter 5, another case study is conducted on the evaluation of fastening mechanisms that include arc welding, soldering/brazing, resistance welding, adhesive bonding, bolt/screw, rivet and snap fits. The selection of joining alternatives is important and more complicated when product life-cycle design is under consideration. In addition to affecting assembly cost and consumption, joining methods will have significant effects on product recyclability and disassembly cost. Applying the proposed framework on fastener selection, a weighted adjustment on the performance of life-cycle stages makes the evaluation comply with environmentally conscious requirements and the concept of life cycle design. From the practice of fastener selection, it is proved that the proposed framework runs well on multiple analysis objects (e.g., seven joining alternatives are evaluated simultaneously), and the framework is obviously capable of analyzing any comparison of design alternatives that is associated with sustainable manufacturing and green product design.

The proposed framework and current research aim at the fulfillment of green product design requirements. Future work associated with further improvements of the proposed framework and the current green product design research has been identified as follows:

1. Development of software for enhancing the operation and calculation of the proposed framework is essential. The software is required to provide a user-friendly interface and facilitate the arithmetic operations on fuzzy numbers.

2. A comprehensive knowledge base containing the current environmental regulations and standards should be created and linked to the developed software. This knowledge base should have a self-learning function so that it may accommodate the rapidly changing environmental requirements.
3. The concept of concurrent engineering may be incorporated with the proposed green product design framework. Efforts should be made to discover how to apply the design coordination approach that is a subdirectory of concurrent engineering for the proposed framework, since green product design is usually based on large-scale engineering projects that involve negotiation between different professionals and the use of conflict resolution.
4. A sensitivity analysis with respect to the measurement scale is another interesting topic. The sensitivity analysis will aim at finding how and how much is the influence by adopting different measurement scales (i.e. [1, 3, 5] and [1, 3, 9]).
5. An analysis of applying different defuzzification methods is worth further study. Defuzzification is the process of turning fuzzy numbers into crisp numbers. Applying different defuzzification methods may result in different rankings obtained from the application of the proposed framework. Consequently, further research on the influence of various defuzzification methods is necessary.

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APPENDIX A

House of Quality

Conventional House of Quality

The House of Quality (HOQ) is the matrix for analyzing customer requirements versus design specifications and it is the fundamental structure of utilizing QFD analysis. In each HOQ, the matrix involves quantifying, comparing, and ranking two attributes of elements. Theoretically speaking, HOQ is the fundamental matrix evaluation tool of the QFD process.

Traditionally, HOQ may be divided into nine subsections (or structurally, nine rooms), which are Customer Needs – *Whats*; Technical Requirements – *Hows*; Correlation of each pair of *Hows*; Importance Ratings of Customer Needs; Competitive Analysis; Relationships between *Whats* and *Hows*; Absolute Score; Relative Score; and Engineering design targets (See Figure A-1). It may be noticed that the triangular shaped correlation matrix is where the term House of Quality comes from because it makes the House of Quality look like a house with a roof.

Room 1: Customer Needs – *Whats*

The content in the *Whats* subsection comprises of the list of characteristics of a product, process, or service, as defined by customers. It is usually the so-called "voice of the customer." In other words, the information collected in this room is to identify what market segments will be analyzed during the process and who the customers are. Some quality tools, such as the affinity diagram and tree diagram, are usually taken for organizing and evaluating the information collected from customers.

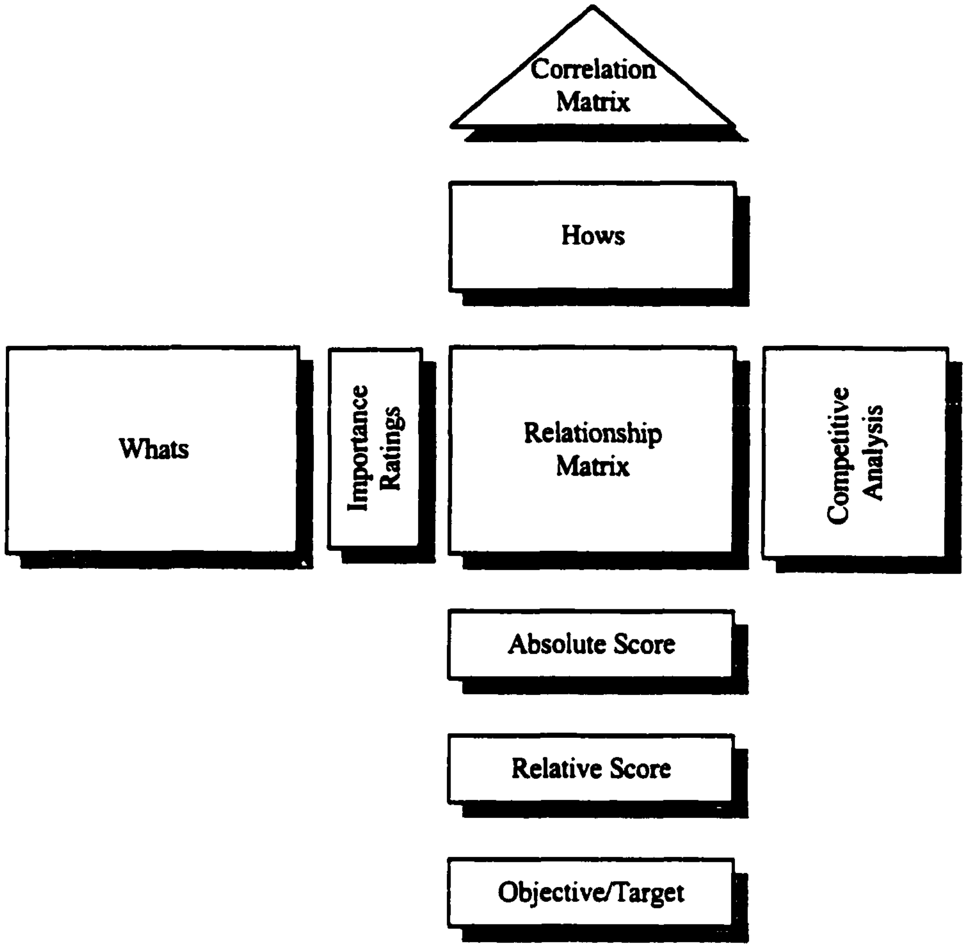

Figure A-1 The structure of House of Quality

Room 2: Technical Requirements – *Hows*

The *Hows* are constructed according to what design characteristics may possibly lead the company to achieve customer requirements. Advised by the cross-functional team, the technical requirements of the planned product or service are listed in this room. The characteristics of technical requirements are stated in the company's language of products and services so that they can be measured and benchmarked against the competition. Alternate names chosen for representing this room may be found in various applications, which include:

- Product expectations;
- Design / Product requirements;
- Corporate expectations;
- Engineering characteristics;

Room 3: Importance Ratings of Customer Needs

This room is actually a numerical table that depicts the relative importance of each customer requirement. Based on the customer assessment and the results derived from the competitive analysis, the importance rating of *Whats* items may be decided. An arbitrary numerical scale, such as 1 to 5, may be adopted to capture the importance ratings. These numbers will be used later for the analysis of relationships.

Room 4: Relationships between *Whats* and *Hows*

In the relationship matrix, the cross-functional design team will analyze the relationship between customer needs and the company's ability to meet those needs. The strength of relationship is usually assigned in a numerical format.

A set of symbols will be used to represent the strength of relationship. For instance, a solid square symbolizes strong correlation, a square with lines stands for medium correlation, a square with dark borders represents weak relationship and a blank is for not related (see Figure A-2).

Symbol	Meaning	Value
■	Strong	9
▥	Medium	3
□	Weak	1
[Blank]	Not related	0

Figure A-2 Symbols of relationship between *Whats* and *Hows*

Room 5: Competitive Analysis

The review of the competitive product or service characteristics in comparison with the ongoing developing product is done in the room of competitive analysis. The competitive assessment is based on the customer perspective (e.g. *Whats* items) as well as the technical perspective (e.g. *Hows* items).

Room 6: Correlation of each pair of *Hows*

The correlation matrix is located on the top of HOQ. The measurement of the interaction between the technical requirements is addressed in this matrix. The purpose of conducting this measurement is to establish potential conflicts early in the planning process and resolve them through trade-off decision making or developing new service technologies that eliminate the bottleneck. Similar to the symbols used in relationship matrix, another set of symbols will be used in the correlation matrix that represents the interaction between the technical requirements (shown as Figure A-3). It will be measured and recorded in the range of strong positive to strong negative, depending on the performance impact between each pair of technical requirements.

Symbol	Meaning	Value
+	Strong positive	3
+	Weak positive	1
-	Weak negative	-1
-	Strong negative	-3

Figure A-3 Symbols of correlation between *Whats*

Room 7: Absolute Score

This matrix performs the calculation of the absolute importance for each technical requirement. This numerical calculation is the product of the relationship value and the customer importance rating. Numbers are then added up in their respective columns to determine the importance for each technical requirement.

Room 8: Relative Score

The relative score can be calculated from the respective absolute score divided by the sum of all absolute scores. These normalized scores allow the design team to easily compare and rank the different product design attributes currently under consideration. In addition, the re-scaled output is on the basis of percentage. Therefore, the outcome is more understandable and acceptable.

Room 9: Engineering design targets

A target value for each technical characteristic will be assigned by the design team and addressed in this room. Target values represent "how much" for the technical characteristic. In order to determine target values, the design team has to examine the performance of the competition's product or service.

APPENDIX B

Analytic Hierarchy Process

The Analytic Hierarchy Process

In this appendix, the computational algorithm used in the Analytic Hierarchy Process (AHP) will be introduced. The materials covered in this appendix are based on Saaty's AHP approach and details may be found in [66][67][68].

Suppose the actual relative weights of n elements are known. In other words, the true pairwise comparisons at one level of the hierarchy with respect to one level higher have been captured. Then we may have the ideal pairwise comparison matrix as:

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \tag{1}$$

where w_i are the actual weights for each element; and

w_i / w_j represent the values of pairwise comparison.

Let the vector of actual weights be $W = (w_1, w_2, w_3, \cdots, w_n)^T$, then the following equation holds:

$$A \bullet W = n \bullet W \tag{2}$$

where n is called eigenvalue of matrix A; and

W is called eigenvector of matrix A.

Since the actual relative weights may not be known, the pairwise comparison matrix is then containing inaccurate (inconsistent) information. For distinguishing the practical pairwise comparison matrix from the ideal one, a notation $\hat{A}$ is adopted.

Similarly, $\hat{W}$ is used for the estimation of W. Then, the following equation may be obtained from (2):

$$\hat{A} \bullet \hat{W} = \lambda_{max} \bullet \hat{W} \tag{3}$$

where λ_{max} is the largest eigenvalue of $\hat{A}$; and

$\hat{W}$ is the right eigenvector.

The λ_{max} may be considered as the estimation of n in (2). Saaty also indicated that λ_{max} is always greater than or equal to n. In addition, the closer the value of λ_{max} is to n, the more consistent are the observed values of $\hat{A}$.

In order to measure the level of inconsistency, the consistency index (C.I.) and inconsistency ratio (I.R.) are utilized. The consistency index may be computed by using the formula [66][67][68] as:

$$C.I. = \frac{\lambda_{mx} - n}{n-1} \tag{4}$$

And, the formula for calculating inconsistency ratio is as [66][67][68]:

$$I.R. = \frac{C.I.}{R.I.} \times 100\% \tag{5}$$

where λ_{max} is the largest eigenvalue of the pairwise comparison;

n is the number of elements being compared;

$R.I.$ is the random consistency index.

The average consistencies for different-order random matrices, namely random consistency index, may be obtained as the table below if the numerical judgments were taken at random from the scale 1/9, 1/8,..., 1, 2,...9 [66].

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	-	-	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Saaty proposed a rule of thumb that the inconsistency ratio should be less or equal to 10 percent for acceptable results. Otherwise, it is recommended that a certain revsion is required in pairwise comparisons.

The eigenvalue method described above is now available in a software product called "Expert Choice" developed by Decision Support Software Inc. Expert Choice has been designed to facilitate the computation in AHP and to generate the overall weights for each criterion. Except for using the computer software, Saaty also introduced two approximation methods for computing overall weights and corresponding inconsistency ratio. One of the approximation methods is the column normalization process that may be found in Saaty [67]. The other method is geometric mean approximation that may also be found in Saaty [68].

APPENDIX C

Fuzzy Set Theory

Fuzzy set theory

Dr. Zadeh was the first researcher to introduce the concept of fuzzy sets in 1965 [87]. Today, non-fuzzy sets are distinguished from fuzzy sets by using the term "crisp". In classical crisp set theory, there are restricted and rigid boundaries. Fuzzy sets, on the other hand, are good at dealing with vagueness by turning the rigid boundaries into the membership function. Usually, the fuzzy set Ã is denoted by ordered pairs:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in U\} \qquad (1)$$

Where U is the universe, whose generic elements are denoted by x;

$\mu_{\tilde{A}}(x)$ is the membership function and $0 \le \mu_{\tilde{A}}(x) \le 1$;

Actually, Fuzzy sets have been regarded as supersets of conventional ordinary sets since Fuzzy sets have been extended to handle the concept of partial truth. For an ordinary set A, $\mu_A(x)$ in (1) denotes the characteristic function of set A in the universe U. The characteristic function is defined such that $\mu_A(x) = 1$ if x is a member of A (i.e., $x \in$ A) and 0 otherwise. That is,

$$\mu_A(x) = \begin{cases} 0 & \text{if and only if } x \in A \\ 1 & \text{if and only is } x \notin A \end{cases} \qquad (1)$$

For distinguishing Fuzzy sets from ordinary sets, the example of defining durability of tires can be used. In ordinary sets, if a tire has greater than 100,000 km performance rating, it may be classified into durable tire set, otherwise it is not. It would not be reasonable for a tire whose performance rating is 95,000 km. In Fuzzy sets, the term of durability will be defined by its membership function shown in Figure C-1.

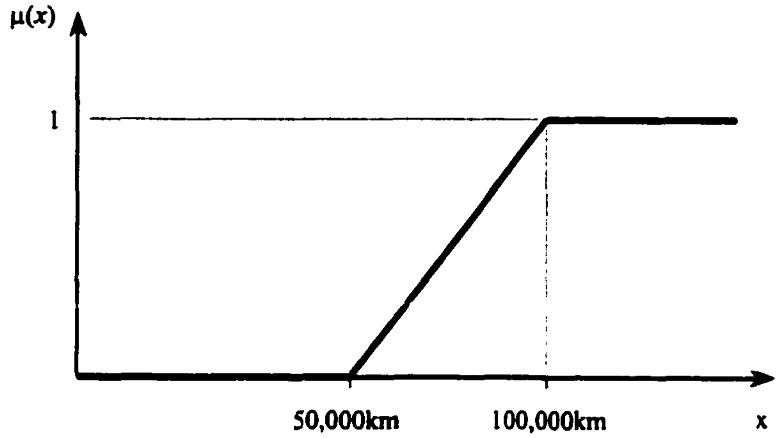

Figure C-1 The membership function of "durability"

Accordingly, the membership function of durability in terms of mathematical definition will be:

$$\mu_{durability}(x) = \begin{cases} 0 & \text{if performance rating is less than 50,000 km;} \\ \dfrac{x - 50{,}000}{50{,}000} & \text{if 50,000 km} \leq \text{performance rating} \leq \text{100,000 km;} \\ 1 & \text{if performance rating is great than 100,000 km.} \end{cases}$$

Therefore, based on Fuzzy sets expression the degree of durability is 0.9 if the tire's performance rating is 95,000 km.

Basic Concepts

For a discrete universe of discourse U = $\{x_1, x_2, \ldots\ldots, x_n\}$, a fuzzy set $\tilde{A}$ can be written as:

$$\tilde{A} = \mu_{\tilde{A}}(x_1)/x_1 + \mu_{\tilde{A}}(x_2)/x_2 + \ldots\ldots + \mu_{\tilde{A}}(x_n)/x_n = \sum_{i=1}^{n} \mu_{\tilde{A}}(x_i)/x_i$$

where the plus sign stands for a union of the elements and $\mu_{\tilde{A}}(x_i)$ is the grade of membership. If U is not discrete, but is an interval of real numbers, the Fuzzy sets Ã can be denoted by using the integration notation as follow:

$$\tilde{A} = \int_U \mu_{\tilde{A}}(x)/x$$

Another important notion and property of Fuzzy sets is the α-cut. An α-cut of fuzzy set Ã is a crisp set A^α that contains all the elements of the universal set U that have a membership grade in Ã greater than or equal to α. That is,

$$A^\alpha = \{x \in U \mid \mu_{\tilde{A}}(x) \geq \alpha\} \qquad \alpha \in (0, 1].$$

If $A^\alpha = \{x \in U \mid \mu_{\tilde{A}}(x) > \alpha\}$, then A^α is called a strong α-cut.

For defining a fuzzy set, we also have to know what is the height of fuzzy set. The height of fuzzy set Ã is the supremum of $\mu_{\tilde{A}}(x)$ over U. That is,

$$\text{Height}(\tilde{A}) = \sup_{x \in U} \mu_{\tilde{A}}(x).$$

If a fuzzy set has the height that is unity, i.e. Height (Ã) = 1, then the fuzzy set is called normal.

Fuzzy Number

A fuzzy set Ã on the real line **R** may be further defined as a fuzzy number if it has the following two properties:

I. the membership function is piecewise continuous or each α-cut is a closed interval for every $\alpha \in (0, 1]$;

II. Ã is a normal fuzzy set.

Therefore, fuzzy numbers can be considered as a subset of fuzzy set theory, while all fuzzy numbers are fuzzy sets, not all fuzzy sets are fuzzy numbers.

There are three different fuzzy numbers often applied to various decision models and control systems which consist of trapezoidal fuzzy numbers, π-function fuzzy numbers and triangular fuzzy numbers. A trapezoidal number $\mu_{\tilde{A}}(x;\ \alpha,\ \beta,\ \gamma,\ \delta)$ may be defined as [32] (Figure C-2):

$$\mu_{\tilde{A}}(x;\ \alpha,\ \beta,\ \gamma,\ \delta)=\begin{cases} 0 & \text{when } x < \alpha \text{ and } x > \delta \\ \dfrac{(\alpha - x)}{\alpha - \beta} & \text{when } \alpha \le x \le \beta \\ 1 & \text{when } \beta \le x \le \gamma \\ \dfrac{(\delta - x)}{\delta - \gamma} & \text{when } \gamma \le x \le \delta \end{cases}$$

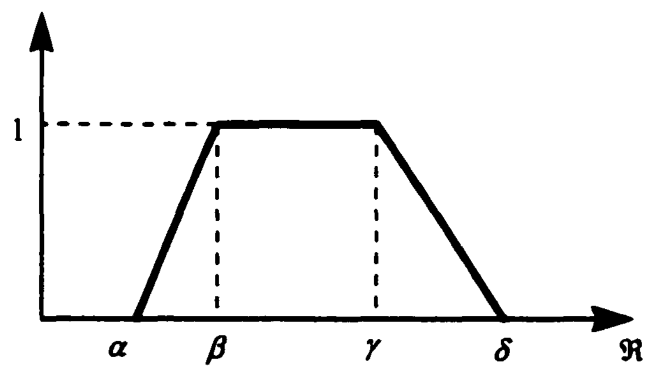

Figure C-2 Trapezoidal fuzzy number

Similar to trapezoidal numbers, a triangular number has only one point whose grade of membership is unity, while a trapezoidal number has a flat region [β, γ]. The general form of a triangular number is represented as [29] (Figure C-3):

$$\mu_{\tilde{A}}(x;\underline{L},M,\overline{L})=\begin{cases}0 & x\le \underline{L}\\ \dfrac{(x-\underline{L})}{M-\underline{L}} & \underline{L}\le x\le M\\ \dfrac{(\overline{L}-x)}{\overline{L}-M} & M\le x\le \overline{L}\\ 0 & x\ge \overline{L}\end{cases}$$

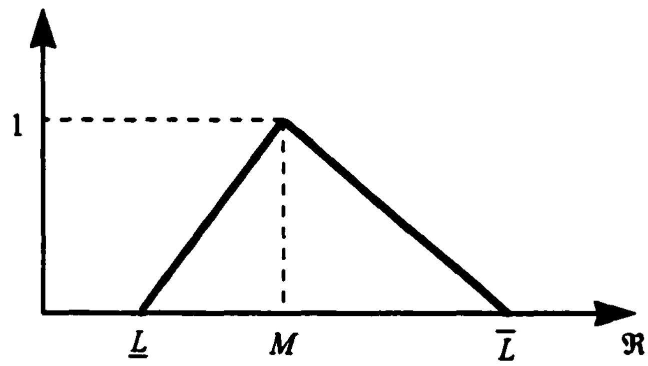

Figure C-3 Triangular fuzzy number

The π-function fuzzy numbers are bell shaped as shown in Figure C-4. There are two parameters that are used for defining a π-function fuzzy number. As the membership function illustrated below, π (x; a, b) states this typical fuzzy number in which a is the point at which π is unity and b is defined as the bandwidth that is the distance between the crossover points where π (x) is equal to 0.5 [47].

$$\pi(x;a,b)=\begin{cases} 0 & x\le a-b \\ \dfrac{2}{b^2}(x-a+b)^2 & a-b\le x\le a-\dfrac{b}{2} \\ 1-\dfrac{2}{b^2}(x-a)^2 & a-\dfrac{b}{2}\le x\le a+\dfrac{b}{2} \\ \dfrac{2}{b^2}(x-a-b)^2 & a+\dfrac{b}{2}\le x\le a+b \\ 0 & x\ge a+b \end{cases}$$

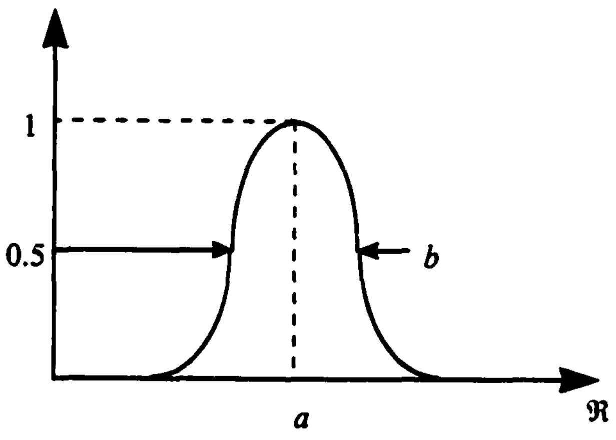

Figure C-4 π-function fuzzy number

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