Selection of Sustainable Product Improvement Alternatives

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Dipl.-Ing. Anthony Halog, MBA

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Referent : Prof. Dr. O. Rentz
Korreferent : Prof. Dr. J. Kowalski

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To my wife Sandy, daughter Germille Benz, parents, brothers and sisters ……

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ACRONYMS AND ABBREVIATIONS

A - *Average*
AA - *Above Average*
ABC - *Activity Based Costing*
ABS - *Acrylonitrile Butadiene Styrene*
ANOVA - *Analysis of Variance*
BA - *Below Average*
BAT - *Best Available Technique*
BOM - *Bill of Materials*
C - *Critical*
CAD - *Computer Aided Design*
CAM - *Computer Aided Manufacturing*
CE - *Concurrent Engineering*
CEO - *Central Executive Officer*
CO_2 - *Carbon Dioxide*
CP - *Cleaner Production*
CR - *Customers' Requirements*
$C_5H_8O_2$ - *Ester*
C_5H_9 - *Alkene*
DFE - *Design for Environment*
DFS - *Design for Sustainability*
DR - *Design Requirements*
DSS - *Decision Support System*
ECM - *Environmentally Conscious Manufacturing*
ECDM - *Environmentally Conscious Design and Manufacturing*
ELU - *Environmental Load Units*
EMAS - *Eco-Management and Audit Scheme*
EMS - *Environmental Management System*
EOP - *End-of-Pipe*
EPS - *Environmental Priority Strategies*
ERP - *Environmental Responsible Product*
EU - *European Union*
FLDSS - *Fuzzy Linguistic-based Decision Support System*
FMEA - *Failure Modes and Effect Analysis*
FMADM - *Fuzzy Multiple Attribute Decision Making*
FMODM - *Fuzzy Multiple Objective Decision Making*
GPD - *Green Product Design*
GSS - *Group Support System*
HOE - *House of Ecology*
HOQ - *House of Quality*
H_o - *Null Hypothesis*
H_1 - *Alternative Hypothesis*
I - *Important*
IA - *Impact Analysis*
IBM - *International Business Machines*
IC - *Indeed Critical*
ILCM - *Integrated Life Cycle Management*
IPDP - *Integrated Product Development Process*
IPPC - *Integrated Pollution Prevention and Control*
IS - *Indeed Superior*
ISO - *International Standards Organisation*
KOSIMEUS - *Kombination von Simulationstool und multikriterielle Entscheidungsunterstützung System*
LCA - *Life Cycle Assessment*

LCAit - *LCA Inventory Tool*
LCC - *Life Cycle Cost*
LCCM - *Life Cycle Cost Management*
LCD - *Life Cycle Design*
LCE - *Life Cycle Engineering*
MADM - *Multi-attribute Decision Making*
MLC - *More or less Critical*
MLI - *More or less Important*
MLS - *More or less Superior*
MRP - *Manufacturing Resources Planning*
NGO - *Non-government Officials*
NI - *Not Important*
NMVOC - *Non Methane Volatile Organic Compounds*
NO_x - *Nitrogen Oxides*
P - *Poor*
PAH - *Poly Aromatic Hydrocarbons*
PMMA - *Polymethyl methacrylate*
POCP - *Photochemical Oxidation Potential*
PROMETHEE - *Preference Ranking Organisation Method for Enrichment Evaluations*
PWMI - *Plastics Waste Management Institute*
QFD - *Quality Function Deployment*
R_{ERP} - *Environmentally Responsible Product Rating*
R &D - *Research and Development*
S - *Superior*
SIMAN - *Simulation Manufacturing*
SIMFACTORY - *Simulation Factory*
SLCA - *Streamlined Life Cycle Assessment*
SO_2 - *Sulphur dioxide*
SPD - *Sustainable Product Development*
SQC - *Statistical Quality Control*
TQM - *Total Quality Management*
TQEM - *Total Quality Environmental Management*
U - *Unimportant*
UBC - *University of British Columbia*
UNEP - *United Nations Environmental Program*
UNIDO - *United Nations Industrial Development Organisation*
USEPA - *United States Environmental Program Agency*
VI - *Very Important*
VOC - *Volatile Organic Compounds*
VP - *Very Poor*
W - *Watts*
WCED - *World Commission on Environment and Development*

ABSTRACT

This work is focused on how industrial companies can be assisted in their design of products so that quality, environmental and cost (QEC) requirements of stakeholders in the life cycle stages of the product system are addressed at an early stage for the eventual purpose of maintaining the firm's competitive advantage and meeting the current concern for sustainability. The consideration of these three design requirements leads to a multi-attribute decision situation with regard to the selection of an optimal product system improvement concept. The main objective of this work is to develop a flexible decision-oriented life cycle approach that attempts to integrate QEC parameters at an early stage of product development. The sub-objectives are to: (1) identify the QEC requirements of a reference product system; (2) determine at which stage of the life cycle phases critical emissions and high cost occur and which product components maximise the satisfaction of the customer's quality requirements; (3) enumerate potential alternatives for improvement to meet the company's strategy for sustainability and assess the capability of each option to achieve each strategic requirement; (4) address the imprecision and incompleteness of data and cost estimates at the early product design stage; (5) apply the developed approach for product improvement of light fitting systems (case example); and (6) substantiate statistically and sensitively the ranking results obtained.

Quality function deployment (QFD) is a proven method for analysing customer's quality requirements systematically in the early stage of product development. Life cycle assessment (LCA) is a recognized method for analysing environmental performance of a product in its life cycle and systems perspective. Life cycle costing (LCC) is an established tool for evaluating all costs associated with a product system in a defined life cycle. Owing to the imprecision and inadequacy of information used for LCA, QFD and LCC at the early phase of product design, a fuzzy linguistic approach is proposed here because it allows to start with little and inexact information, and it handles linguistic variables in a mathematically well-defined way. Out of these 4 methods, a conceptual approach was developed which is made up of four major phases. Phase I involves the identification and documentation of QEC requirements' information extracted from modified QFD, LCA, and LCC methods. Phase II entails the generation of alternative concepts for product system improvements and the construction of a sustainable concept comparison house or matrix where fuzzy terms were adopted to describe relationships and importance. In Phase III, a fuzzy linguistic decision support system, which uses a fuzzy linguistic heuristic algorithm, was developed and applied to evaluate and select the optimal sustainable product improvement alternative. Phase IV involves sensitivity and statistical analyses of the ranking results obtained.

The primary output of this work is the developed conceptual methodology itself. Specific to the case study, the ranking results of alternative options for system improvement with respect to individual considerations to environment, cost and quality including their interrelationships are reported. For instance, when one assessed the options for system improvement from environmental, customer's product quality and cost perspectives simultaneously, the development of new products with lower material consumption is the optimal sustainable choice. The contributions of this work are as follows: (1) it integrated quality, environmental and cost attributes in the presence of imprecision and inadequacy of design data inputs at the early stage of product improvement; (2) it provided companies a life cycle approach that is holistic and preventive for the design of product systems; (3) it developed a sustainable concept comparison matrix and a heuristic algorithm to strategically select the optimal alternatives for sustainable product improvement or development; and (4) it used statistical analysis to check the ranking established.

1 Introduction

Worldwide competition in today's global economies has brought significant challenges to many companies that want to meet continuously changing specific requirements of present and potential customers. Some of the most critical issues that manufacturing firms should consider to remain competitive in the market are maintaining high quality products, lowering costs and prices, decreasing product cycle time and protecting the environment.

In the past, quality has played a vital role, other than price or cost, in determining organisational strategic competitiveness. It is viewed that product quality is very important in customers' satisfaction. In view of this, organisations, particularly manufacturing firms, have designed, improved or developed their products as well as their processes to meet the critical quality requirements. Nowadays, environmental concern is becoming increasingly important in the global society (both within the industries, within the governmental organisations, and within the public). One important reason for this upsurge in concern for ecology is due to the report that was published by the World Commission on Environment and Development, which focuses on the need for sustainable development as a strategy for further economic development [WCED, 1987]. The Brundtland Commission defined sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Although this definition is broad in scope, it is up to the concerned interest groups to establish specific actions such as cleaner production projects and sustainable industrial development of the manufacturing sector. Most of the corporate leaders in industrialised countries recognised that the environmental responsibilities are as central to business success as are the quality and costs of their products and processes [Rushton, 1993; Quinn 1996]. Rushton [1993] commented that companies take steps to create new environmentally oriented products because the environment has become a potent market force - offering opportunity as well as risk. Additionally, a survey of 220 executives by Booz, Allen, & Hamilton [1991] and another of 90 CEO's by Berglund [1991] reported that managing environmental risk and opportunity is one of the highest strategic priorities for the 1990s and that, for that matter, the early part of the 21st century. Even the International Chamber of Commerce had issued 16 environmental principles for firms to consider in their environmental responsibilities when making decisions about plant location, process and product design and other operating factors [Angell & Klassen, 1999]. Government authorities in several countries are also establishing policies and regulations to address environmental concerns and to give incentives to companies to take responsibility for their products throughout the life cycle while at the same time environmentalists are actively protesting and lobbying when the environment is at stake.

Through this heightened environmental awareness fuelled by public interest groups and media, consumers are becoming increasingly concerned about the environmental "friendliness" of the products that they purchase. Statistics showed that consumers have incorporated the environmental issue other than quality and cost in their buying decisions. Antonides, Van Raaij, & Fred [1998, p. 501] reported that in European Union (EU) countries alone, the consumers' environmental concern had increased from 1986 to 1995, from 74% to as high of 87% based on their surveyed European consumers. EU consumers expressed that protection of the environment and suppression of environmental pollution is an immediate and urgent problem. Likewise, the United Nations Industrial Development Organisation (UNIDO) has also a similar view. UNIDO pointed out that if developing and transitional economies, e.g. Philippines, would like to fully benefit from the increasing liberalisation of world trade, industries in these economies must meet the demands in terms of quality and environmental management systems, and consumer protection.

Due to this added concern in environment other than quality and cost, it is expected that the responsibility of manufacturing organisations becomes increasingly tougher. It could be foreseen that consumers (stakeholders in general) would demand that their products should be environmentally oriented, in addition of being affordable and of high quality [Gupta and Sharma, 1996]. Design and manufacturing of ideal products, which meet the customer requirements, cost less and are environmentally friendly, is becoming the goal of most manufacturing firms. Thereby, manufacturing firms that can immediately address the three aspects of quality, environment, and price will surely remain competitive in the future. Firm's responsiveness to quality, environmental, and even health and safety issues can determine not only its competitive position, but also its very survival [Sarkis, 1998; Hongen and Xianwei, 1996; Berglund, 1993].

With the rationale stated above, environmental, quality and economic considerations are important ingredients for the design of successful marketable products. Manufacturing firms should satisfy not only the product requirements of the end-consumers but the environmental demands of governments and buyers as well so that these firms can gain sustainable competitive advantage in the market place. This requirement for environmental stewardship, in particular, is raising the stakes for design decisions and posing unprecedented challenges for manufacturing companies. The ecological requirements are forcing manufacturers to re-examine their approaches to a wide range of concerns, including product and packaging design, material selection, production processes, and energy consumption, to name just a few. In many industries, particularly large ones, the focus has been on overall system design and quality management, largely because it is estimated that at least 66% of the total costs of product development, manufacturing, and use are determined and committed at the initial design stage prior to production [Asiedu & Gu, 1998; Oakley, 1993; Dowlatshahi, 1992; Züst and Wagner (1992); Fabrycky & Blanchard, 1991; National Research Council, 1991;

Fabrycky, 1987]. Nevertheless, in spite of the imprecision and incompleteness of design data and information at this early stage, decisions are made regarding the type of resources and manufacturing processes to be used, with these decisions also ultimately determining the nature of waste streams [Heinzle & Hungerbühler, 1997; Graedel & Allenby, 1995; Van Weenen and Eekels, 1989].

Hence, manufacturing firms would be at a better competitive position if they have a conceptual framework or methodology on how they would consider environmental goals in addition to cost and quality objectives for the design of products and their corresponding processes at the very beginning of the design stage. Many researchers have suggested that in order to increase eco-effectiveness in products, new methods and instruments for integrating environmental requirements into the early phases of the product design process must be developed [Lye, Lee and Khoo, 2001; Kobayashi & Fushiya 1999; Alting, Hauschild & Wenzel, 1998; Luttropp & Züst, 1998; Frei & Züst, 1997; Van Weenen, 1997; Fiksel, 1996]. Additionally, Heinzle et al. [1997], Weidenhaupt & Hungerbühler [1997] and Mak, Mühle & Achini [1997] emphasised the urgent need for early design and decision tools in the manufacturing industry in spite of inherent high uncertainty involved due to inadequate knowledge, missing data and complex interactions for the system at the beginning.

1.1 Problem Statement

Given the described need above, the research problem is focused on how industrial firms can be assisted in the design of product systems so that environmental, quality and economic requirements of stakeholders in the life cycle phases of the system are addressed at the early stage of product development process. It is assumed here that manufacturing companies prefer to produce and sell products that are of high quality, environmentally oriented and at minimal cost. On the other hand, customers want goods of superior environmental and quality performance at the lowest feasible cost. The consideration of these three design aspects leads to a multi-attribute decision making situation with regard to the selection of the most appropriate product system improvement concept to be deployed on the succeeding stages of product development. For example, for the sustainable improvement of a light fitting system which is the case study of this work, some of its quality, cost and environmental attributes are simple surface structure, simple to install, low life cycle cost, reduced emissions of toxic substances and reduced global warming potential. The question is on how these environmental, quality, and cost requirements can be considered at the early stage of product development in the presence of uncertainty of information so that the best option for product improvement is chosen and adopted for the purpose of maintaining the firm’s competitive advantage as well as meeting the current concern for sustainability.

1.2 Objectives of the Study

To deal with the problem, the main objective of this work is to develop a decision-oriented life cycle approach that enables the integration of cost and quality factors together with environmental considerations at the early stage of product development so that alternatives can be consistently compared and the optimal option is chosen. Through this way, the manufacturing company can demonstrate its commitment to environmental stewardship and economic competitiveness.

To meet the main objective, the sub-goals are:

1. identify the environmental, quality and cost requirements of stakeholders for a given product system;
2. determine at which stage of the life cycle phases the critical emissions and high costs occur and which product components maximise the satisfaction of the customer's quality requirements;
3. enumerate potential opportunities for improvements available for implementation to meet the company's overall strategy for sustainability and make an assessment of the capability of each option for improvement to achieve each strategic requirement or attribute;
4. account the unavailability and inaccuracy of quality and environmental related data and information, and of cost estimates at the early product design stage;
5. apply the developed methodology for choosing the optimal sustainable product design concept for the improvement of a light fitting system; and
6. confirm statistically and sensitively the ranking results obtained.

1.3 Methodological Approach

The first phase of the methodology is to identify and document the requirements or attributes based on the reference product (refers to the company's existing products) with respect to customer's quality requirements, environmental performance and cost in a life cycle perspective through the use of modified or simplified QFD, LCA, and LCC methods. The environmental requirements are defined synonymously here as environmental impact categories and obtained using the inventory analysis and classification steps of the Life Cycle Analysis (LCA) method. Life cycle assessment (LCA) is a proven method for analysing environmental performance of a product in its life cycle and systems perspective. One of LCA's limitations is that it does not account for non-environmental aspects such as product quality and cost. On the other hand, the customers' quality and cost requirements' information is obtained from modified Quality Function Deployment (QFD) and Life Cycle Costing

(LCC) methodologies, respectively. Quality function deployment (QFD) is an established method for analysing customer's quality requirements systematically in the early stage of product development. The disadvantage of QFD is that it does not account environmental considerations. Life cycle costing (LCC) is a well-established tool for evaluating all costs associated with the product system as applied to a defined life cycle as in LCA. This method provides information on which processes or components that are costly to the consumers and manufacturers. These three methodologies are discussed extensively in Chapters 3, 4 and 5.

In the second phase, the identified critical requirements (attributes) are then used as basis to generate alternative concepts for product improvement. These options for improvement could be obtained through systematic methods such as group brainstorming, which is a popular method for doing creative tasks in manufacturing organisations such as developing products. After knowing the proposed alternatives, the forecasted environmental and cost performances of the options for improvement are estimated by analogy with respect to the reference system. Then, a sustainable concept comparison house or matrix is constructed where the capability of each of the options for improvement to meet the critical requirements and the importance of QEC requirements provided by decision makers or designers are modelled using defined fuzzy linguistic variables. A fuzzy linguistic approach is used here because it allows one to get started with imprecise and incomplete design information used for LCA, QFD and LCC at the early design stage e.g. estimated costs and emissions information, and it handles linguistic variables in a mathematically well-defined way.

In the third phase, a fuzzy linguistic decision support system, which employs a fuzzy linguistic based heuristic algorithm, is developed and used to aid in the selection of the optimal sustainable product improvement concept. In the last phase, sensitivity and statistical analyses are conducted to confirm the preference or ranking of alternatives.

1.4 Significance of the Study

In addition to the rationale of the research pointed out at the beginning, the present work is particularly essential to developing countries such as the Philippines so that it can aid them to manufacture and market their products in accordance to the requirements demanded by international customers. Moreover, in the Philippines, environmentally conscious production and manufacturing is gradually making its way into industrial firms through the current flagship program in Cleaner Production and Pollution Prevention of Department of Science and Technology (DOST) to address the consequences of environmental issue. With the proposed methodology, Philippine industrial firms would be able to know how to improve their products and processes sustainably and will be able to respond to challenges posed by van Weenen [1997]: a strong emphasis on sustainable product development should be placed on the future of developing countries.

In addition, this work is intended to assist companies, both in developed and developing countries, in addressing the issue of environmental protection, in addition to cost and customers' product quality for the overall organisational competitive performance. It is also expected that through this study, small and medium industrial companies will be encouraged to implement environmental management systems such as ISO 14001 in addition to the well known ISO 9001 quality system. The conceptual methodology is also thought to be useful for manufacturing engineers and sales or marketing staffs, as the eco-efficiency or sustainability of the products is assessed by considering cost, quality, performance and impact on the environment concurrently. Generally, the developed methodology, particularly the third phase, is also expected to provide a framework for industrial firms to assist in their selection of materials, processes and technologies.

1.5 Limitations of the Study

The study is focused on environmental, quality and economic requirements of concerned stakeholders in general, however the identified requirements are not exhaustive. It is not the intention of this study to conduct LCA, LCC, and QFD studies comprehensively but rather to know and show on how these three methodologies can be potentially integrated to address the simultaneous consideration of quality, environmental and cost requirements. With regard to environmental aspects, emphasis would be on determining the environmental attributes derived from the environmental impact categories established in LCA. The approach used in this research did not follow a comprehensive LCA but rather an abridged LCA to account for less data requirements, few days of effort and particularly its usability at the early stage of a product development process. With respect to quality, it is only focused on those customers' requirements that are believed to be relevant and likely will give a firm a competitive advantage. Although it is far better to consider the concerns of all stakeholders (customers, shareholders, regulators, and interested communities), the stakeholders are defined here to include only end-customers because it is the most important source of pressure for companies to install environmental plans [Henriques and Sadorsky, 1996]. For economic consideration, this work considered the estimated life cycle cost and the purchase price of the product rather than the individual cost factors. The streamlining of LCA, LCC and QFD methodologies were made because of their data-intensiveness and lack of accurate and complete data.

This study covers only the early stage of product development process where the detailed product/process design phase is not conducted. Explicitly, this study is only limited up to the decision making stage to determine which product improvement concept should be further deployed in the succeeding stages of product development. The House of Quality (HOQ) is the only matrix that was used in this study. Additionally, establishment of QFD matrices for design deployment, process planning, production planning, maintenance planning and retirement or disposal planning are not made in the present study.

Moreover, the case study's results in this work largely depend on the accessibility of primary and secondary data. The gathering of information is primarily conducted through indirect contact with Lumilight Electric Product and Lighting, Inc. rather than a planned structured direct interview in the said Philippine company. The collected data was only limited and needed to be supplemented from other data sources.

Lastly, the major drawback in this type of study is the lack of direct access to accurate data for conducting LCA, LCC and QFD analyses. Problems with regards to veracity of data for all types of materials and processes, especially data concerning special chemical substances used might limit the validity of the case study's results.

1.6 Outline of the Study

This study is subdivided into 11 chapters, which are structured as follows:

Chapter 2 to Chapter 6 cover the review of related literature and the necessary theoretical background to assist the reader in understanding the different concepts introduced and following the line of thinking for the developed conceptual methodology in Chapter 7. Selected and related topics about quality and environmental management in relation to the design of products and processes, quality function deployment, life cycle assessment, life cycle costing, fuzzy linguistic, multi-criteria or multi-attribute studies, etc. are discussed. Chapter 2 discusses product planning and development concepts including the relevance of eco-efficiency in the design of product systems. Chapter 3 explains the importance of quality considerations in concert with competitive advantage, how QFD can assist in achieving it and presents related previous QFD studies conducted. Chapter 4 discusses the different emerging methodologies and concepts concerning environmental considerations in the design of products and processes. It also tackles how a design for environment could address the company's environmental stewardship and discusses the popular method of life cycle assessment and reviews previous LCA related studies. Chapter 5 describes the concept of life cycle costing with relevance to design for economic feasibility. Chapter 6 presents the concepts of fuzziness, fuzzy set theory, fuzzy linguistic variables, different multi-criteria methodologies including a non-exhaustive review of previous fuzzy related studies. After reviewing the literature and the required theoretical background, Chapter 7 considers in detail the proposed approach for the evaluation and selection of sustainable product system improvement concepts under fuzzy data uncertainty. Chapter 8 applies the developed methodology in the case of a light fitting system. Chapter 9 reports the outcome, results of the case study and the necessary analyses and discussion. Chapter 10 concludes the study, presents the implications and research contributions and recommends some future possible extensions of this work. Finally, Chapter 11 provides a four-page extended synopsis.

2 Product Planning and Development

This chapter discusses the concepts associated with product design, integrated product development process, concurrent engineering and sustainable product development. This section does not provide an in-depth discussion of product planning and development but is rather limited only to those concepts that are considered relevant.

2.1 Product Design and Definition

With increasing competitive pressures and rapidly changing markets, the reduction in product development cycle time has become an essential goal for manufacturing firms. Equally important to this are the goals of continuous improvement in product quality, environmental quality, cost reduction and responsiveness to the "voice of the customer." Other than these, response to increasing product design complexity, flexibility, and variety should also be included as objectives for new product development [Molina, Kusiaka and Sanchez, 1998, p. 400]. Siegwart and Senti [1995, p.260] cautioned that the success or failure of a manufacturing company is closely dependent on the success or failure of its product development. Product development is an expression of the desire to survive as a company in the long run [Andreasen and Hein, 1987, p.29]. Roy & Riedel [1997] commented that the most significant fertile ground for firms to pursue new competitive advantage should come from product design.

Product design is the process that harnesses the company's creative energies to satisfy customer and market requirements. Roughly speaking, the task of product design consists of [Andreasen et al., 1987, p. 25]:

- Detailed analysis of the need
- Determination of the type of product
- Design in principle
- Elaboration of the product and proving its function
- Maturation of the product (fixing details to suit volume of sales and production methods)
- Adaptation of the product (adjustment to those problems which turn up when it is launched onto the market, together with any subsequent adaptation)

Design processes allow the product development team to fulfil the quality, environmental and economic requirements specified in the business plan. Product definition places a critical role in product and process design. A product definition is a statement of the features that a specific product should have when development is completed. It provides the basic specifications that the product development team relies on throughout the design process. This step is crucial to clarifying where environmental, quality and cost requirements fit in hierarchy of product requirements that designers must address. In the case when environmental requirements, other than quality and economic, are not factored into the basic definition, designers will have great difficulty finding time to work on them and will not know how to make appropriate trade-offs with other design objectives.

2.1.1 Definition of Design and its Features

There are as many different definitions of design as there are writers on the topic. For instance, according to Deiter [1991], "Design establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have been previously solved in a different way." Pugh [1991] and Urban & Hauser [1993] see design in a larger context, as Total Design - "the systematic activity necessary, from the identification of the market/user needs, to the selling of the successful product to satisfy those needs - an activity that encompasses product, process, people and organisation". Dym [1994] points out that design problems are open-minded insofar as they usually have many acceptable solutions and are ill structured because their solution cannot normally be found by routinely applying a mathematical formula in a structured way. He defines design as "the systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints".

Design is central to manufacturing industry. That is even more true in today's climate of high technology and consumer expectancy. Design has a direct impact on a company's bottom line. It determines not only the functional performance and reliability but also the cost of the product. Design impacts on every part of a manufacturing company's business and equally those same parts impact on design.

Several important features of engineering design include the following:

- Design links a market need or an expected market opportunity to a product or process.
- Successful execution of design can result in various acceptable solutions but usually, only one optimal solution.
- Design largely involves, invokes and depends upon the creative parts of the humans. It is also an intellectual pursuit.

- Proper design for the environment minimises demands upon the environment and loads on the environment both in the short or long run.

2.1.2 Design and Development

The design process proceeds from a set of stated requirements for a given product or system and evolves through (1) conceptual design (i.e., the establishment of performance parameters, operational requirements, and support policies), (2) preliminary systems design (sometimes called advanced development), and (3) detail design. This process generally begins with a visualisation of what is required and extends through the development, test, and evaluation of an engineering or prototype model of the system. The output constitutes a configuration that can be produced or constructed directly from specifications, supporting documents, and a database.

The engineer's role in design and development involves a variety of functions that are dependent on the type of system and the extent of new development necessary. These functions may include all or any combination of the following:

1. Accomplishing functional analyses and allocations to identify the major operational and maintenance support functions that the system is to perform.

2. Establishing criteria (i.e., qualitative and quantitative technical parameters, bounds, and constraints) for system design.

3. Evaluating alternative design approaches through the accomplishment of cost-effectiveness analyses and trade-off studies.

4. Preparing system, development, product, process, and material specifications.

5. Selecting components for the system and recommending supplier sources.

6. Assisting the purchasing and contracting functions in the preparation of supplier specifications and contractual documentation.

7. Preparing functional design layouts, drawings, parts and material lists, standards, and so on, with the objective of thoroughly defining the product or process through documentation.

8. Assessing the design through predictions, analyses, and the performance of periodic design reviews.

9. Developing breadboards, engineering models, and prototypes for system test and evaluation purposes.

10. Developing system software (computer programs), associated databases, and related documentation required to define, design, test, produce, operate, and maintain the system.

11. Developing system and component test specifications and procedures, and accomplishing specific tests to ensure that all design requirements are met.

12. Performing design modifications as necessary to correct deficiencies and/or to improve the system design.

2.2 Methods for Generating Product Ideas

In an effort to have good and new ideas for product development, many methods have been developed to generate them. These include focus groups, attribute listing, forced relationships, brainstorming, reverse brainstorming, and problem inventory analysis [Hisrich and Peters, 1978, pp. 57-61; Douglas, Kemp and Cook, 1978, pp.64-70). Because good new product ideas come from diverse sources and often in bizarre ways, these methods are not to be taken as the end-all for idea generation. Rather, these methods should be viewed as a mechanisms by which new product ideas can, in general, be more easily generated. Reader [1996, pp. 258-259] provided a more comprehensive list of idea generation techniques and this is also found in Appendix D.

2.2.1.1 Focus Group Interviews

Focus group interviews have been used in many aspects of product research since the 1950s. A focus group interview consists of a moderator leading a group of people through an open, in-depth discussion. This is much different from a group interview in which the moderator simply asks questions to solicit responses from participants. In the focus group, the moderator focuses the discussion of the group on the new product area in a nondirective manner.

In addition to generating a new idea, the focus group is an excellent means for the initial screening of ideas and concepts. Recently, several procedures have been developed so that more quantitative analyses can be used in interpreting the focus group results. With increased use and the development of more procedures, the focus group is an increasingly valuable method for generating product ideas [Hisrich et al., 1978, p. 58]

2.2.1.2 Attribute Listing

This technique consists of listing the existing attributes of a product idea or area. These attributes are then modified until a new combination of attributes emerges that will improve the product idea or area. For instance, a small company manufacturing pallets used for shipping or moving a product on a conveyor along an assembly line wanted to devise a better product. It listed the attributes that defined the existing pallets, such as wood composition, rectangular runners, and accessible on two sides by a forklift. The wood composition could be changed to plastic, resulting in a cheaper price; the rectangular wooden runners could be replaced by cups for easier storing, and the cups would allow the new pallet to be accessible on all four sides for each of pick-up. Through attribute listing, this small company achieved a new pallet idea that had much improved product characteristics.

One major drawback to attribute listing is that it focuses on the product at hand. It cannot be used in all new product situations. It may even stifle imaginative thinking to some extent. Yet, as in the case of the pallet manufacturer, it is often useful method for developing a new product idea.

2.2.1.3 Forced Relationships

A third method of generating new product ideas is forced relationships. In this technique many new ideas are first listed. Then, as the name implies, the new product ideas are considered in pairs. By considering one idea in relation to every other, new ideas are often generated [Hisrich et al., 1978, p.59]. Even though this technique is not in wide use, it is a good, systematic procedure to see whether there are any new products that stem from a combination of existing products. These new products would then naturally fit into the existing product line and management expertise.

2.2.1.4 Brainstorming

The technique evolves from the principle that people can be stimulated to greater creativity by meeting with others and participating in organised group experiences. Top management of a company meets frequently in small groups of between six and ten to generate new product ideas. This method often produces a large number of ideas. This is especially true when the meetings, lasting about an hour, focus on a specific area. There are rules to be followed for most effective use of management brainstorming. Basic guidelines and rules to follow in conducting this technique include the following [Molina et al., 1998; Sutton & Hargadon, 1996; Hisrich et al., 1978, p.60]:

□ No criticism. Negative judgements must be withheld until later.

□ Freewheeling is encouraged. The wilder the idea, the better; it is easier to tame down than to think up.

□ Quantity is wanted. The greater the number of ideas, the more the likelihood of useful ideas.

□ Combinations and improvements are sought. In addition to contributing ideas of their own, participants should suggest how idea of others could be used to produce still another idea.

Brainstorming technique is the most popular for doing creative tasks in manufacturing organisations like developing products, overhauling business systems and improving manufacturing.

2.2.1.5 Reverse Brainstorming

This approach is a modification of the preceding technique. The objective of reverse brainstorming is to take a particular product, such as dishwasher, and generate a list of shortcomings. This list of negative attributes then provides the direction for discussion on new products and product improvements. The general advantages and disadvantages of this approach are similar to the management of brainstorming technique. The limitation of this approach is that it is based on the problems of a product as perceived by producers. There is no indication whether these are important problems for customers.

2.2.1.6 Problem Inventory Analysis

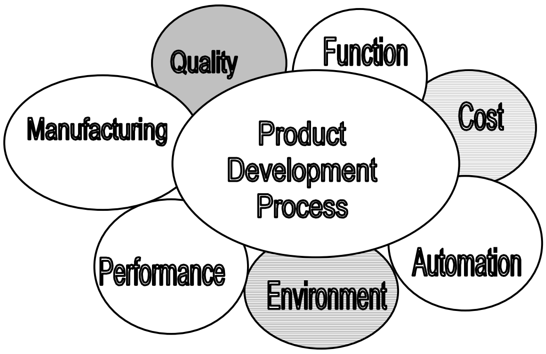
This is a method to generate new product ideas that uses customers in a manner similar to focus groups. However, instead of asking the customers to generate new product ideas themselves, customers are provided with a list of problems from a general product category, such as food. The customers are then asked what products have this particular problem. This method is often more effective than a focus group because it is much easier for customers to relate known products to suggested problems and arrive at a new product idea than to generate a new product idea with minimal guidance.

2.3 Integrated Product Development

Integrated product development process (IPDP) addresses the product, the process and the business aspects of the product to be developed. The product is what to be delivered to the customers. The process is how this product is to be produced. Finally, the business issues cover how we are to function to develop, produce and deliver the product. IPDP is a disciplined computer-integrated product and manufacturing process development methodology that combines marketing, finance, design, engineering, manufacturing, purchasing, and suppliers in the development from concept initiation to customer delivery [Wu, Yuen & Fuliang, 1995; Hjort, Hananel & Lucas, 1992]. It is a process whereby all functional groups that are involved in a product life cycle participate as a team in the early understanding and resolution of key product development issues including quality, economy, environment, manufacturability, reliability, maintainability, and safety [Fiksel, 1996, p. 66; Andreasen and Hein, 1987, p. 21]. IPDP progresses from opportunity identification, evaluation and selection, concept (product, process, business) development, subsystem/detail design (product, process, business), pilot production and finally production. The main objective of IPDP is to achieve the highest customer satisfaction at the lowest possible cost. Similarly, companies that adopt IPDP also practise the approach of “concurrent engineering”

(CE) or simultaneous engineering, in which the different engineering disciplines work in a parallel, coordinated fashion to address life-cycle requirements [Evanczuk, 1990].

Furthermore, in most industrial companies, the product development process needs to accommodate a multitude of design parameters. The design teams should concurrently account for cost, quality, environment, improved functionality, performance and other issues important to the product's success in the marketplace such as those shown in Figure 2-1. With regard to environmental consideration, a handful of firms are currently attempting to build environmental awareness into their product development efforts. Fiksel [1996, p.3] strongly believe, in meeting the 27 Principles of Rio Declaration, integration of different design aspects at the earliest stages of product and process development can be the only way to fully satisfy these philosophies in an economically viable fashion.



Source: Veroutis & Fava, 1996 ; Molina et al., 1998, p. 400.

Figure 2-1 Design Considerations in the Product Development Process

In the present study, the concept of IPDP serves as a framework for integration of quality, environmental and cost requirements because of its holistic approach to product development where representatives from marketing, production, environmental department, product development and other relevant departments are working together in teams throughout the process. Although the above figure shows many design aspects to consider, the present study is only interested to deal with three aspects, which include product quality, cost, and environment.

2.4 Concurrent (Simultaneous) Engineering

As pointed out in the previous section, concurrent engineering is related to integrated product development process. This concurrent view becomes necessary to overcome the limitations of sequential engineering steps. Eversheim [1990] defined concurrent engineering as "an organisational strategy" with the idea to shorten the time of product design by simultaneous planning of product and production. Concurrent engineering may also be referred as simultaneous or parallel engineering. It is a systematic approach to integrated and concurrent development of a product and its related processes, that emphasises response to customer expectations and embodies team values of co-operation, trust and sharing in such a manner that decision making proceeds with large intervals of parallel working by all including life-cycle perspectives early in the process, synchronised by comparatively brief exchanges to produce consensus [Gunasekaran, 1998; Molina et al., 1998]. Concurrent engineering is a critical component of total quality management (TQM) in which product and process designs are accomplished simultaneously. One element in a TQM process is the use of quality function deployment (QFD), which is extensively discussed in Chapter 3 and relates customer requirements to design characteristics for the eventual purpose of manufacturing products that meet those requirements. Gunasekaran [1998] explored the possible use of concurrent engineering to design products, production systems, and production planning and control system for improving productivity and quality in process industries. He further suggested that new manufacturing concepts such as statistical process control (SPC), QFD, TQM, manufacturing resources planning (MRP) and many others should be applied not only in discrete manufacturing industry but also to process industries. In the case of process industries, raw material selection is important as this influences the processes required to produce the final product and hence determines the equipment design, design of the plant and operations and the type and amount of environmental wastes. He also added that process simulation and QFD could be used as tools for concurrent engineering to improve productivity and process performance.

In the present study, it is assumed that the concept of concurrent engineering is being practised in a company in the design of products with specific emphasis to quality, environmental and cost requirements.

2.5 Sustainable Product Management and Development

The Brundtland Commission defined sustainable development as a process that “meets the needs of the present without compromising the ability of future generations to meet their own needs” [Boswell, 2001; Fiksel, 1996, p. 4]. Sustainable development is a process in which the exploitation of resources, the direction of investments, the orientation of technological development, and the institutional changes are all made consistent with future as well as present needs [Khanna and Kulkarni, 1996, p. 322]. The World Commission on Environment and Development [WCED, 1987] stressed the need for sustainable development and stated, that sustainable develipment is “not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional changes are made consistent with the future and the present needs”. Sustainable development requires the integration of environmental protection in the socially oriented market economy and the latter’s development into an ecologically and socially oriented market economy [Enquete, 1995, p.15]. The implied question in this model of development is how to assure continued industrial growth without adverse ecological impacts, which was a major theme of the 1992 Earth Summit in Brazil. The industrial sector has practised this thrust by demonstrating its environmental stewardship through implementing pollution prevention measures or focused its effort through the lens of eco-efficiency. Eco-efficiency involves the delivery of competitively priced goods and services that satisfy human needs and bring quality in life, while progressively reducing ecological impacts and resource intensity through the life cycle to a level in line with the earth's estimated carrying capacity. Industries operationalise the concept of sustainable development via cleaner technologies and products (cleaner production). Nowadays, an increasing number of manufacturing companies is gradually embracing sustainable industrial development to include the natural ecosystems in which they operate. By sharing responsibilities for the environment at all organizational levels within companies, substituting toxic compounds and the application of renewable energy and environmentall sound technologies, new environmental management instruments are developed [Baas, 1996, p. 212]. Products are being designed, produced, distributed, used and disposed with minimal (or none) environmental and occupational health damages, and with minimal use of resources (material and energy).

Within an organisation, sustainable management of product systems can be divided into 3 levels [Hanssen, Rydberg & Roenning, 1996]. These are:

1. *Sustainable company management* deals with the integration of environmental performance and resource efficiency aspects in all relevant functions of the company. Related to sustainable management, strategic decisions are made to influence the long-term business relationships of a company. Strategic decisions will of course be part of all strategic activities and might also be connected to other activities in a company. Strategic activities are customarily directed towards the long-term development of a company, such as product planning, annual activities with development of the strategic plan, involvement in new markets, buying of companies, changes in the production structure etc. Most of these activities are initiated and driven by top management in a company with input from the operating departments. Some specific examples of strategic activities important in manufacturing firms include the integration of environmental issues in the strategic plan and business plan; integration in all or selected product development projects; development of an LCA database for its own raw materials and processes; integration in supplier auditing programs, and education of employees in systems engineering, LCA and sustainable product development [Hanssen, Roenning and Rydberg, 1995].

2. *Sustainable product planning* deals with the integration of environmental, social and economic aspects in product planning activities.

3. *Sustainable product development (SPD)* involves the incorporation of environmental, social and economic parameters without sacrificing other parameters in the design of products and process. Broadly speaking, sustainable product development is a resource-, context- and future-oriented product development, aimed at providing elementary needs, a better quality of life, equity and environmental harmony [van Weenen, 1997]. With the concept of sustainable product development, a product-oriented approach to improved environmental performance is directed towards the same goal as that of sustainable development: antropogenic activities that are compatible with ecosystems [Rydberg, 1996, p. 403]. Examples of issues of strategic importance in a sustainable product development project might include:

    - development of new technology by research and development (R & D) activities
    - change of suppliers
    - new transport systems
    - application of new materials (e.g. change from steel to composite materials)
    - installation of new production equipment.

2.5.1 Collaboration with External Parties

For several reasons, it is important to involve the participation of external parties in a sustainable product development project, without giving these groups all information that a new product is under development. The participants who should be more or less systematically consulted in this type of project are the relevant customers, suppliers of raw materials and services, environmental authorities and non-governmental environmental organisations. For instance, R&D of BASF Company improves its collaboration with outside parties such as customers and end users to foster environmentally sustainable activities in its research effort [Scott, 2001].

Customers generally have the best source of information about how the reference product is most likely used. They are also the focal source of information about customer requirements in a QFD study, although it must be clear that customers are not homogeneous with respect to their priorities. Involvement of some of these customers in a project might be of great help in marketing a new product. Through this participation, customers also become aware of the significance of environmental issues.

Suppliers could also be involved in a SPD project. The concept of life cycle engineering shows that it is critical to cooperate with suppliers to find new and better solutions to environmental problems. However, there is also a disadvantage in involving representatives from suppliers too early in a project. Many suppliers will naturally have a conservative approach to the project in evaluating new materials and processes, as they naturally will protect their own status and market shares. Suppliers' participation in this SPD project should thus be restricted to obtaining data from existing materials and processes, and data for alternative solutions that might be proposed by the project team or the supplier itself. But the project team should be free to find other solutions outside the domain of existing suppliers.

Moreover, several other stakeholders could have also considerable influence on the public opinion related to products and environmental problems, e.g. environmental authorities and non-governmental environmental organisations. Participation of representatives from these parties could result to better implementation of the project. Collaboration with these external groups should at least be involved in determining the evaluation criteria for improvement, determining potential market volumes, and documenting the environmental performance and user instructions.

2.5.2 Sustainable Decision Making and Strategies

A real company's commitment to become more sustainable in all its business activities will require the involvement of top management and the most important internal stakeholders of a company. If a company sees a challenge and new possibilities for long term growth in developing, producing, marketing and selling more sustainable products, this decision will require the participation of all departments and at different levels in the company. To get more sustainable solutions, it is necessary to meet requirements without overemphasising any one factor. A product with improved environmental performance will be a more sustainable solution only if it is implemented in the market as a substitute for lower performance. Environmental management at company level encompasses all levels of plant organisation and leads to an integrated overall management system. Environmental management means continuously optimising a company's entire product line in accordance with specific environmental aspects, e.g. by designing products to be recyclable, by integrating environmental protection in products and production processes, by optimising transport, by reducing waste in terms of both quantity and quality, by promoting employee involvement, and by means of external communication [Enquete, 1995, p. 16].

To develop and introduce a more sustainable product system, decisions have to be taken on different levels in the society such as the level of private citizens and the level of companies in business [Hanssen, 1995 and 1997]. On the private level, the main strategies to approach a higher level of sustainability are to: (1) reduce the consumption of non-renewable energy carriers and products which are not crucial to the quality of life; (2) select the most environmental efficient products in a life cycle perspective, and use those products in a proper way; and (3) contribute to higher material efficiency through waste separation and material recovery systems. On company level, the main strategies towards more sustainable business activities are to (1) innovate new and more environmentally sound products continuously [Enquete 1995 & 1997], (2) require new and more environmentally efficient solutions from other business partners, (3) select the right materials in products, and choose suppliers with superior environmental performance of their products, and (4) focus more on life cycle economy, and less on short term profit.

Furthermore, Hanssen [1997] suggested that to approach a target level of 80-90% of improvements in environmental performance, increased co-operation from the different levels of the society is needed for the purpose of: (1) increasing material efficiency by closing the loop between material recovery and use of recovered materials, (2) developing and implementing new energy systems based on renewable energy carriers with high efficiency, (3) improving the efficiency in logistic systems and reducing the demand for transport of goods and persons, (4) increasing the innovation capacity in the society by demanding much more material and energy efficient products, and (5) improving information exchange and knowledge about the performance of the total system between the different actors along the life cycle of the product.

2.6 Brief Chapter Conclusion

In this study, the term “sustainable” refers to the consideration of environmental and economic requirements at a long-term perspective (e.g. 20 years) in any undertaking such as in the case of sustainable product development. Sustainable product development involves the incorporation of environmental and economic parameters without sacrificing other parameters in the design of products and process. In this study, it is assumed that the concepts of integrated product development process and concurrent engineering serve as frameworks for integration of quality, environmental and cost requirements because of their holistic approach to product development. Moreover, since design involves, invokes and depends upon the creative parts of the human experience, brainstorming technique will be adopted in the proposed conceptual methodology developed in Chapter 7 because it stimulates people for greater creativity to generate many ideas and secondly, it is the most popular for doing creative tasks in manufacturing organisations like developing products, overhauling business systems and improving manufacturing.

The next three chapters will discuss the three critical design parameters (quality requirements, environmental impacts and costs) in conjunction with early product development.

3 Quality Consideration and Quality Function Deployment

One of the three design parameters that are being considered in this study is the customers' product quality requirements. Among the overall goals a company pursues, quality has shown in numerous studies to be among the most important ones. Quality, in simple terms, is meeting or conforming to the customer requirements. This definition suggests that both the needs and the perceived needs of the customer should be explored. Quality is the customer's perception of and evaluation of the properties he or she observes and attributes to the product, together with the set of his or her value norms used as a basis for evaluation of the product [Andreasen et al., 1987, p.171]. Imai [1986] claimed that if one takes care of quality, the profits would take care of themselves. The reason for this is that quality is strongly associated with both the effectiveness and efficiency of a manufacturing company. Effectiveness is a measure of how well the company lives up to the market expectations. Efficiency is a measure of how well company resources are utilised and deployed in the various tasks of maintaining and developing the business, e.g. cost and time efficiencyc, use of knowledge, etc. Quality has become one of the critical competitive strategies in global market as exemplified by Japanese firms. Many Japanese manufacturing firms believed that one key to their successful products is their emphasis on quality of conceptual design where at least 66% of the total product costs are already committed at an early stage despite that only 5-10% of the total project costs are actually spent [Moerup, 1993, p. 5].

3.1 Quality

Although the word quality has different connotations when used by different people and the definition has also undergone changes over time but the central concept remains the same, namely, quality of a product is satisfactory when the product is able to satisfy the requirements of the consumer. Alternatively, it is a set of attributes of a product which, if incorporated into a product meant for a specific purpose or use, will satisfy a consumer. An earlier accepted definition of quality has been: *The quality of a product is the degree of conformance to applicable design specification and workmanship standards*. Obvioulsy, this definition did not conern itself with the element of time and would not say if the product will retain its quality over a given time. Also it would say anything about the product's performance under a set of given conditions of use. Both these elements were not part of quality but inherent in the definition of reliability, since reliability [Misra, 1992] is defined as the ability that a product will perform a specified function over a specified time without failure under the specific conditions of use. However, bad quality does definitely affect realibility because inferior workmanship would definitely shorten life of the product and thus its reliability. Quality cost is generally considered as the concern of manufacturing department alone and responsibility of production manager. This limited definition of quality enlarged with time and with the emergence of several quality experts' mostly statisticians, who successfully demonstrated that improved quality meant improved business.

There are others, mostly engineers, who not quite agree with statisticians and have the notion that it is basically an engineering design effort, by which the performance of a product can be increased. They may as well be called as proponents of reliability and see quality as a necessary but not sufficient characteristic. There are others (mostly statisticians) to whom quality is all pervasive and they consider reliability effort as a part of quality programme.

Quality professionals themselves have often struggled with the definition of quality for some quite time. Crosby [1979] defined quality as conformance to requirements. Juran and Gryna [1980] provides a simple-looking definition of quality as fitness for use. Deming [1982] defined two different sets of quality, viz., quality of conformance and quality of performance. Quality of conformance is the extent to which a firm and its suppliers surpass the design specifications required to meet the customer's needs. Quality of performance is the measure, arrived at through research and sales/service call analysis, by assessing of how well products perform in the marketplace. This measure, in fact, is synonymous with the concept of reliability and leads to redesign, new specifications, and to a product improvement programme on continuous basis for any manufacturing concern.

Moreover, quality is defined as the total composite product and service characteristics of marketing, engineering, manufacture, and maintenance through which the product and service in use will meet the expectations of the customers [Feigenbaum, 1983]. It is the totality of features and characteristics of a product or service that bears on its ability to meet a stated or implied need [ISO 8402, 1986]. Badiru and Ayeni [1993, p.2] defined the quality of a product as the balance of interest between the producer's capability and the customer's need. The quality of any product or service has two distinct but interrelated aspects: (a) quality of design, and (b) quality of conformance to design. Quality of design is a measure of how well the product is designed to meet the customer requirements. It refers to activities which assure that new or modified products and services are designed to meet customer needs and expertations and are economically achievable. If the quality of design is low, then the product will not satisfy the requirements. Quality of design is primarily the responsibility of Research and Development (R&D), Process Engineering, Market Research and related groups. Quality of conformance to design, on the other hand, is the extent to which the product achieves the quality of design [Muhleman, Oakland and Lockyer, 1992, p. 97]. It refers to manufacturing products or providing services which meet previously determined and clearly defined specifications. Production, Scheduling, Purchasing, and Shipping departments have primary responsibility for quality of conformance.

Taguchi [1986] offers a different definition of quality, which is the loss imparted to the society from the time a product is shipped, other than any losses caused by its intrinsic functions. He has helped to focus the interest and attention on the importance of design in producing high quality products at low cost. He divides quality control efforts into two categories: on-line and off-line quality control. On-line involves diagnosis and adjustment of the process, forecasting and correction of problems, inspection and disposition of product and follow up on defectives shipped to the customer. The off-line quality control is quality and cost control activities carried out at the product and process design stages during the product development cycle. Off-line quality control is an intense engineering focus on building quality into the product, starting at the very beginning of product and process design. Off-line quality control is concerned with [Taguchi, 1986]:

1. Correctly identifying customer needs and expectations,
2. Designing a product which will meet customer expectations,
3. Designing a product which can be consistently and economically manufactured,
4. Developing clear and adequate specifications,standards, procedures and equipment for manufacture

Taguchi's concept of quality, relates to determining the ideal target values (parameter design) and evaluating losses due to variation from the target value. The concept of quality loss function focuses on evaluation of quality due to variation from the target (also called losses due to functional variation). Thus the objective of a quality program is to minimise total losses to the society- both the producer and the consumer.

Whatever the definition of quality one might settle for, but there is no denying by any one that to ensure the basic objective of high quality, a designer must be able to translate the needs of the consumer into an engineering design, including specifications and tolerances; the production engineer must be able to design a production process that would produce the product meeting these specifications and tolerances, while ensuring minimum emissions or pollution of the environment. Not only that, but manufactuers must be able to procure the raw materials and energy in order to produce the product, keeping overall costs and wastes to a minimum. The quality manager must be able to test and evaluate the product being produced. Finally, feedback from the consumers must be obtained for improving the product. Afterall the product is intended to serve the consumer and it should be the consumer who should feel satisfied in the end. If he does not, then it is a waste of money, manpower, material and energy.

3.1.1 Quality Planning

Quality planning is at the heart of total quality control (TQC) and is an activity aimed at preventing quality problems and includes:

- Establishing quality guidelines
- Builduing quality into the design
- Procurement for quality
- Control of nonconforming material
- Ensuring in-process and finished product quality
- Inspection and test planning
- Handling and follow up of customer complaints
- Education and training for quality

Quality guidelines are established by knowing the customer requirements and once these are clearly understood and it is determined that the company policies, procedures, and objectives are in conformity with these requirements, one may proceed to develop an effective quality plan. If necessary, these procedures and objectives can be revised. Design quality is ensured by comparing the proposed design with the customer requirements, including reliability and maintainability considerations. A design is finally reviewed for producibility and inspectability since it is always possible to design product that satifies the customer's requirements but cannot be manufactured with the existing technology. Design quality requires establishing specifications for all important quality characteristics and developing formal product standards. Work instructions and detailed operating procedures also form a part of this activity.

Inspection and test planning is always integrated with the design and production activities as they directly influence the quality of the product and involve fixing up of inspection points, classification of characteristics according to their criticality, design and procurement of inspection and test equipment, and development of inspection instructions and test procedures. These activities are usually performend by quality control or test specialists and are usually aimed to achieve the following targets:

- Determination of product acceptance relative to customer requirements
- Determination of product reliability
- Qualification of a vendor, process, machine, etc.
- Verification of other requirements.

3.1.2 Total Quality Management

Here again, there are several definitions. Tobin [1990] defines total quality management (TQM) as a totally integrated effort for gaining competitive advantages by continuously improving every facet of organisational culture. Witcher [1990] highlights important aspects of TQM using the following explanation.

Total: signifies that every person in the firm must be involved (possibley even customers and suppliers).

Quality: indicates that customer requirements are met fully.

Management: represents that the senior exectuvies are fully committed.

Feigenbaum [1983] defines TQM as the organisation-wide impact of total quality control. Feigenbaum [1991] gives a more complete definition of TQM: “A total quality system is defined as one which embraces the whole cycle of customer satisfaction from the interpretation of his requirements prior to the ordering stage, through to the supply of a product or service of an economic price and on to his perception of the product after he has used it over an appropriate period of time. TQM covers all activities of the overall management function that determine the quality policy, objectives and responsibilities and implement them by means such as quality planning, quality control, quality assurance and quality improvement within the quality system [Wheaton and Schrott, 1999, p.188; Zink, 1998, p. 36]. In fact, TQM entails application of management techniques, quantitative methods and human resources to improve the material services supplied to an organisation, all the processes within the organisation, and the degree to which the requirements of its customers are met, now and in the future. In fact, quality management provides an overall philosophy stressing on systematic, integrated, consistent, organisation-wide perspective involving everything and everyone and focuses mainly on satisfaction of internal and external customers, seeking continuous improvement of all systems and processes at the same time. It stresses on optimal life-cycle cost and applied management methodologies to target improvements. The important elements of this philosophy are the prevention of defects and an emphasis on quality in design. Thus the main aim of TQM includes the elimination of losses and the reduction of variability. It also stresses the development of relationships between employees, suppliers and customers.

According to Hakes [1991], a good TQM must have the following characteristics: leadership; total customers satisfaction; total involvement; ownership; error prevention; commitment; continuous improvement; training and education; reward and recognition; and cooperation and teamwork. Thus, there is no denying that management commitment, training, teamwork, leadership, motivation, etc., each would have a vital and complementary role to play in establishing a total quality environment. It is true that there is no enterprise that cannot be improved upon. The most important contributions in creating a total quality environment is to recognise the need for continuous improvement programmes using the following tools and techniques:

-Data collection form

-Benchmarking

-Cause and effect diagrams

-Tree diagram

-Histogram

-Scatter diagram

-Affinity diagrams

-Brainstorming

-Flowchart

-Control chart

-Pareto diagram

Several people believe that TQM is perhaps the only way of assuring customers that they will get what they want first time, each and every time.TQM is also necessary since there is enough evidence to show that it works. If it were not so, the leading firms like IBM, Xerox, 3M, Toyota, Ricoh, Canon, Hewlett-Packard, Nissan and many others may not have been so successful. TQM is not just to meet customer requirements but to provide them satisfaction. Some companies, like Rover cards, have extraordinary customer satisfaction as their corporate mission. Among other features, customer requirements may include delivery, availability, reliability, maintainability and cost effectiveness. While dealing with a supplier-customer relationship, the supplier must establish a marketing activity charged with this task. The marketers must, of course, not only understand the requirements of the customer completely, but also their own ability to meet customers' demands. Within organisations, and between customers and suppliers, the transfer of information regarding requirements is often very poor or is totally absent. Therefore a continual examination of the requirements and the ability to meet them is the price of maintaining quality. In fact, TQM philosophy relies very much on using the knowledge-based as an asset in an organisation. Everyone including the top management needs to be educated and trained in order to do a better job.

Today several companies are developing their own quality systems with the aim of:

- Reducing first time failures;
- Reducing the costs of customer claims;
- Getting things right the first time; and
- Improving service to the customer and to increase competitiveness.

Moreover, manufacturing firms have adopted Total Quality Management (TQM) as a key element of their business goals and initiated the use of TQM methods, such as Quality Function Deployment (QFD), Design for Quality (DFQ) and Design for Manufacturability (DFM).

3.2 Design for Quality

Substantial improvements in product can only be made if the quality aspects of design are looked at in particular and in a scientific manner, just as it was the case with design for assembly, design for environment, design for manufacture and design for reliability. Current attempts to define design for quality (DFQ) include definitions which are very tool specific, for instance, experimentation. In the quality design approach, all efforts are directed at reducing the uncertainty of the product in the design stage (via Taguchi's statistical methods). Design for quality is a knowledge system (part of the total design science) that gives all the necessary knowledge to a designer to achieve the requested quality of a product or process. Some authors suggest that design for quality contains elements from all aspects of product development, from corporate strategy to detailed decisions.

3.3 Quality Function Deployment

QFD is considered a key enabling technology for concurrent engineering (Armacost et al., 1994). Franceschini and Rossetto [1997] and Islam and Liu [1995] described QFD as a customer driven decision support tool, which helps the manufacturers to incorporate the customer requirements into product and process development. Mclaughlin and Stratman [1997] stated that QFD could be used to translate customer requirements into product specifications and in turn to specify the process capabilities required to meet those customer requirements. QFD uses certain problem-solving and planning tools drawn from a set called the "Seven Management and Planning Tools". This methodology originated in 1972 at Mitsubishi's Kobe shipyard site, Japan. Then, Toyota and its suppliers developed it further and used it for a rust prevention study [Wolfe, 1994; Wasserman, 1993; Hauser and Clausing, 1988]. However, others argued that QFD has developed from the roots of value analysis and value engineering.

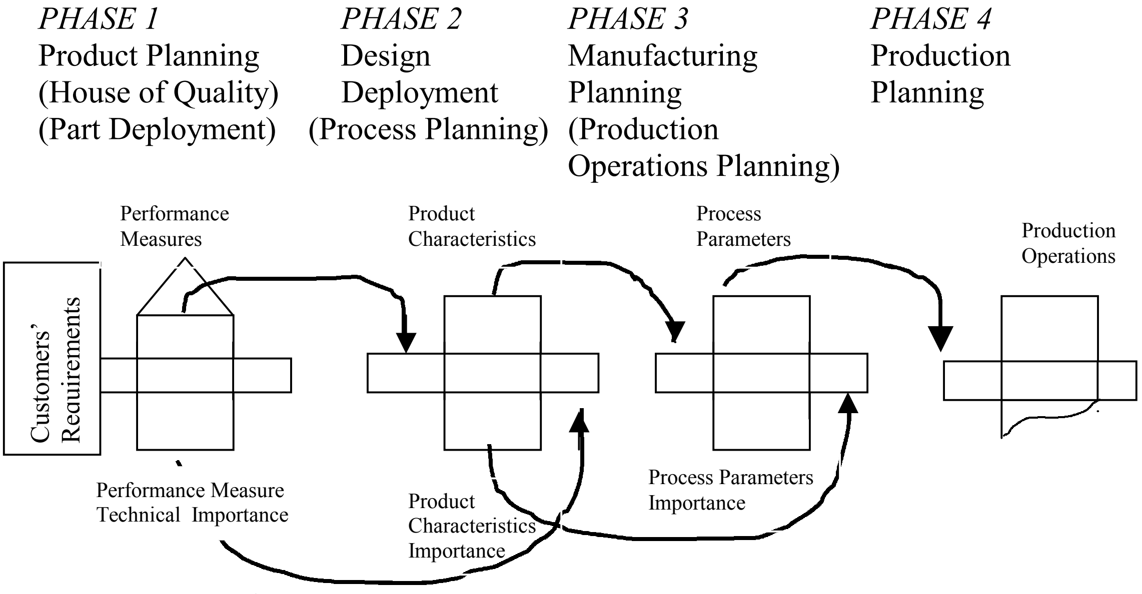
Moreover, QFD is said to be a Japanese method for structuring a process and recently has been recognised as an important strategic planning tool. It is considered a means to deploy the voice of the customer into search for substitute technologies, into the selection of the best opportunities and the development of products and/or services. After the concept of QFD was introduced in the US through auto manufacturers and parts suppliers [Ansari and Modaress, 1994; Sullivan, 1987], many firms, such as Procter & Gamble, BMW, Raychem, Daimler Chrysler, Digital Equipment, Roche Diagnostics, Hewlett-Packard, AT&T, General Motors, Siemens and Ford, applied this methodology to improve communication, product development, and measurement of processes and systems.

In a broader sense, QFD is a tool to organise large quantities of seemingly unrelated information coming from all stakeholders to a product and/or service development effort, to allow to focus on the relevant information and to provide insights into the wants and needs of the stakeholders [Hjort et al., 1992]. It is a system for translating stakeholders' requirements into appropriate company requirements at each stage from research and product development, to engineering and manufacturing, to marketing/sales and distribution. QFD is a proven methodology to achieve total customer satisfaction, which is used by numerous companies with great success.

However, one of deficiencies that are particularly significant in the present study is its lack of explicit mechanism to include environmental impact assessment in the course of product development or improvement [Zhang, Wang & Zhang, 1999].

3.4 Basic Concept of QFD

The basic concept of QFD is to translate the desires of customers (customers' quality requirements) into product design or engineering characteristics, and subsequently into parts characteristics, then to process plans and eventually into production requirements (as shown in Figure 3-1). In phase 1, the customer needs are defined and prioritised, competitive opportunities are analysed, the product is planned to respond to opportunities, and critical characteristic target values are established. In phase 2, critical parts and assembly are



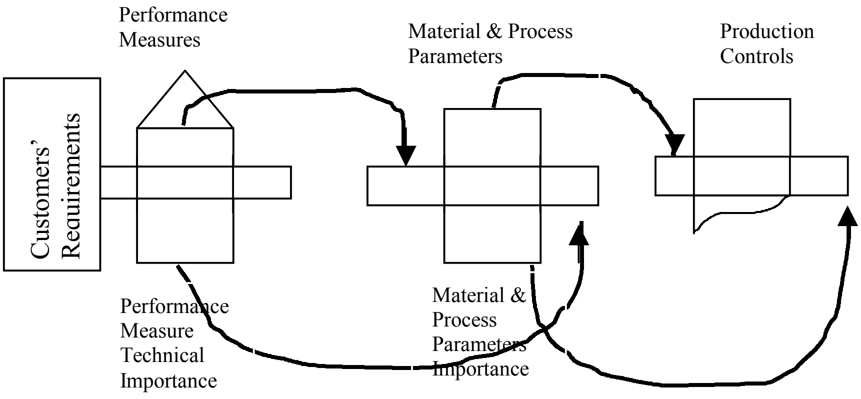
Source: Cohen, 1995, p. 311

Figure 3-1 Four-phase QFD Model

identified, and then critical product characteristics are flowed down and translated into critical part characteristics and target values. In phase 3, critical processes and process flows are determined, production equipment requirements are developed, and critical process parameters are established. In phase 4, critical part and process characteristics are determined, process control methods and parameters are established, and inspection, test methods and parameters are established. Figure 3-2 below is a suggested QFD model for continuous process industries such as glass, food, mouthwash and detergents. Phase 2 and phase 3 in Figure 3-1 are combined as both material and process characteristics which directly influence the end-product characteristics (measures) [Hofmeister, 1990].

The QFD methodology uses matrices to organise information and shows multiple relationships between different kinds of information. These matrices are used for identifying customer requirements (CRs) and establishing priorities of design requirements (DRs) to satisfy the customer requirements (CRs) [Crow, 1996; Hauser et al., 1988]. This means that in addition to identifying which characteristics are most critical to satisfy customers, it also provides us with targets for these characteristics based on competitive benchmarking.

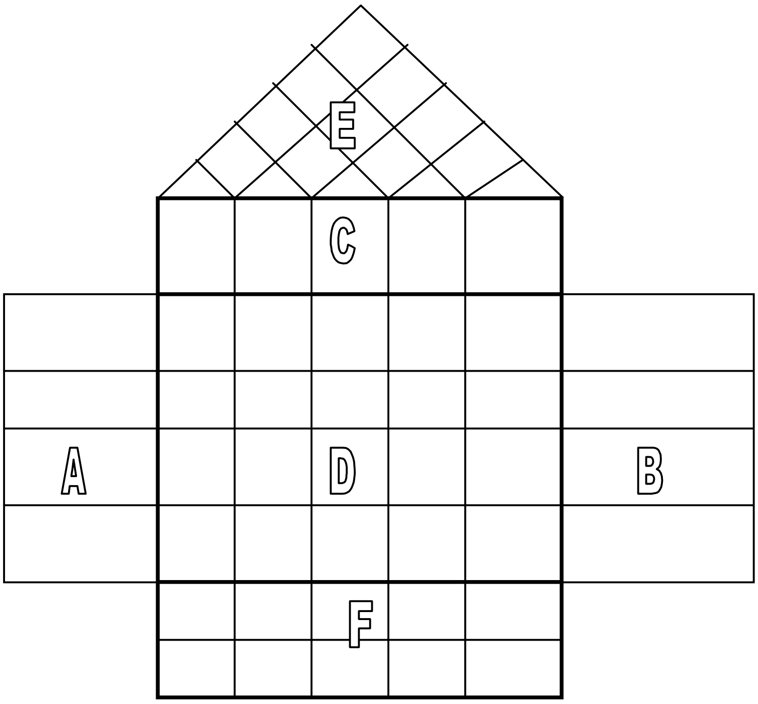
PHASE 1	*PHASE 2*	*PHASE 3*
Product Planning (House of Quality)	Design and Process Planning	Production Planning



Source: Hofmeister, 1990.

Figure 3-2 QFD Model for Continuous Process Industries

HOQ consists of six basic steps: (1) identify customer's attributes or requirements, (2) identify technical features (counterpart characteristics) of the requirements, (3) relate the customer's requirements to the technical features, (4) conduct and evaluate competing products, (5) evaluate technical features and develop targets and (6) determine which technical features to deploy in the remaining stages of the production process [Tottie and Lager, 1995; Graessel and Zeidler, 1993; Rijsenbrij and Bauer, 1993]. Figure 3-3 shows the typical chart of HOQ with the descriptions of its labelled parts as follows:



Source: Cohen, 1995, p.12.

Figure 3-3 House of Quality (HOQ) Chart

- *Area A* includes the customer requirements (CR) organised into appropriate classifications. CRs are the product's requirements in customer's terms. The structure is usually determined by qualitative research such as structured interviews and surveys. Molina et al. [1998, p. 401] suggested several approaches to determine customer needs and requirements. Capturing this "voice of customer" is one of the most important contributions QFD makes to the development of successful products and systems. According to the literature, it is stated that the average number of defined customer needs varies between 5 to 10 at a primary level, 15 to 30 at a secondary level, and 50 to 250 at a tertiary level [Ekdahl & Gustaffson, 1997; Cohen, 1995; Mizuno and Akao, 1994 and Ohfuji, Ono & Akao, 1990]. In some of the extreme cases the number of stated needs is up to 1000 [Cohen, 1995]. However, it is difficult to speculate about the differences and these variations might be due to the different purposes of QFD projects. For instance, if a company is working with quality assurance it is likely that more customer needs are included than in the case of product improvement projects.

- *Area B* is the planning matrix. This section contains four main types of information: first, the quantitative data which indicates the relative importance of the wants and needs to the customer; second, the company's competition of current offerings (evaluation of competing products will enable designers to seek opportunities for improvements and allows priorities to be set in the design process); third, strategic goal setting for the new product or process; and fourth, computations for rank ordering the customer wants and needs.

- *Area C* is for technical specifications or design requirements (DR). DRs are the design attributes expressed in the language of the system engineer, designer, and developer. The DRs must be measurable and meaningful, since the output will be controlled and compared to objective targets. Going from user requirements to technical specifications involves translating from the qualitative requirements into quantitative measurable characteristics. This step is a difficult aspect of QFD.

- *Area D* is the relationship matrix that indicates the extent to which each end-user concern has been addressed by a design control parameter. Relating the customer's requirements to the technical features shows the strength of the relationship between them and whether the attributes are addressed fully and properly or whether the final product will have difficulty in meeting customer needs. The intersection of each technical specification column in *Area C* and customer requirement row in *Area A* forms a field in the middle of the house. These fields contain the correlations between the pairs. Parameters that directly address a requirement are indicated by ✔; parameters that weakly or indirectly address a requirement are indicated by ✓. Strong conflicts are indicated by ✖ and weak conflicts are indicated by ×. Alternatively, a rating scheme of 1-3-9 (weak-medium-strong) to indicate the degree of strength between customer requirements and design requirements, or any other appropriate rating systems may be used for assessing correlation between CRs and DRs.

- *Area E*, the "roof" of the house, captures the trade-offs between the various engineering parameters. Here, strong conflict is indicated by ✖. Weaker conflicts would be indicated by ×. Strong synergy is indicated by ✔, and weaker synergy by ✓. Alternatively, a rating scheme of 1-3-9 (weak-medium-strong), or any other appropriate systems may also be used for the correlation among DRs. This area is the most difficult to determine and usually left by those who are doing QFD studies because it requires deeper study just to know the trade-offs.

- *Area F* is the technical matrix and used for the new design. Evaluating the technical features and developing targets will introduce quantitative measures on product consistency, perceived quality, and other features desired by the customers and users. Determining the features to deploy will confirm identifying the characteristics that have a strong relationship to customer needs. These characteristics will need to be deployed in the design and production process to ensure that the voice of the customer is heard, and that the right product is produced effectively. Targets are set for all control parameters that determine the new design along with cost, technical difficulty (risk), and relative importance of achieving each target. This provides management with a valuable means to direct resources by showing the expert's best estimates of the costs and benefits of each improvement in the product or current system design. It also allows producers to evaluate their existing product lines against the competitors using the technical measures.

Moreover, QFD assigns priority to product improvements and reduces development time by minimising changes and concentrating on defect prevention rather than defect detection, as discussed by Ermer [1995], Zultner [1993] and Delatore, Prell & Vora [1989]. It helps to introduce the idea of quality in the early phases of the requirements cycle and to re-evaluate quality considerations throughout the project's entire life cycle. Its use facilitates the process of concurrent or simultaneous engineering, encouraging teamwork, to work towards a common goal of insuring customer satisfaction [Hongen et al., 1996]. Through a series of interactive matrices, QFD can be employed to address virtually any business situation requiring decision involving a multitude of criteria, requirements or demands. Some QFD softwares available in the market are listed in Appendix C.

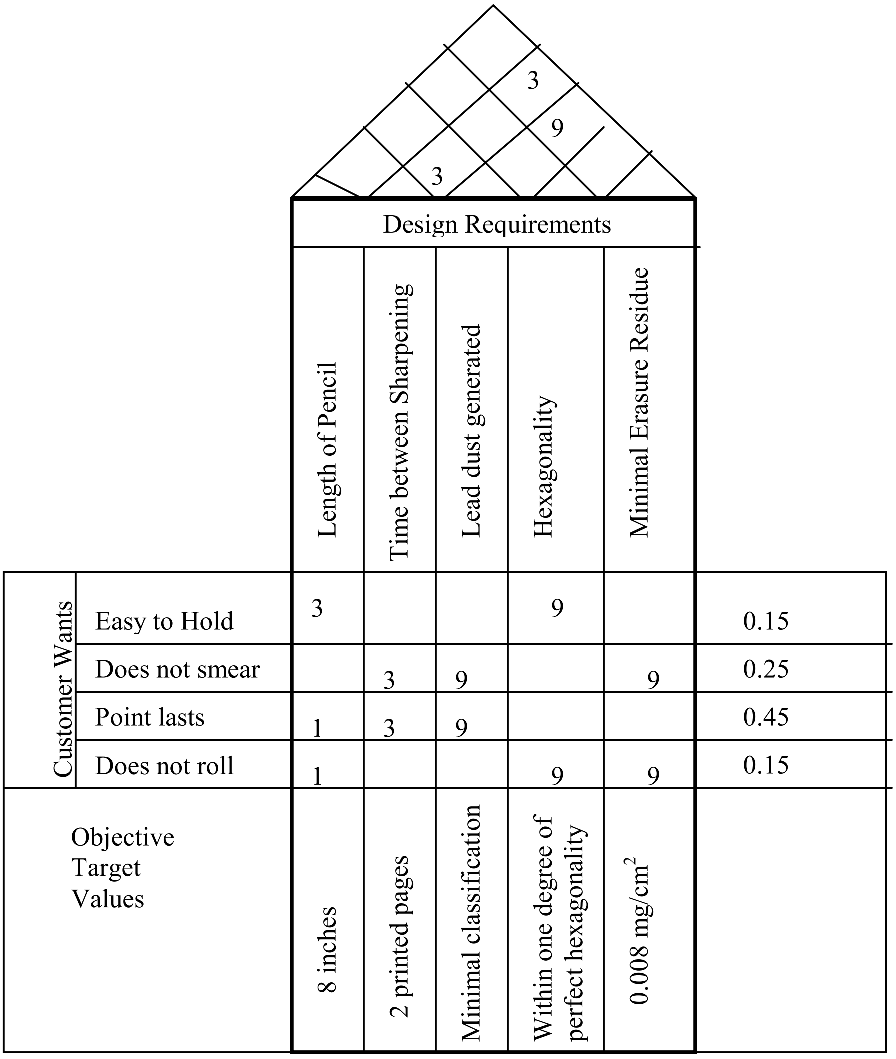
Since the steps to the matrix of CRs versus DRs are general, then it is applicable also to environmental situations with little modification, provided they are based on a relevant recognition and understanding of the stakeholders involved in the process. Mclaughlin and Stratman [1997] suggested that an actual QFD matrix could also include external requirements such as regulatory and environmental issues.

In the present study, out of those 6 areas in Figure 3-3, the ideas behind parts A, B, C, and D are useful for the modified HOQ methodology that is presented in Chapter 7.

A QFD Example

The product planning matrix or the HOQ for a hypothetical writing instrument is illustrated in Figure 3-4. For instance, the important customer requirements, or wants (Area **A**) which include *easy to hold, does not smear, point lasts, and does not roll* are listed on the left hand side of the matrix. For each customer requirement, say for instance, *point lasts*, the design team must respond to this need by identifying the important engineering design requirements (Area **C**) such as *time between sharpening, lead dust generated, and minimal erasure residue*, which if the requirements are fulfilled, would satisfy this need. At the right most side of Figure 3-4, Area **B** provides the importance or weights of the critical customer wants.

In this QFD example, the rating scale of 1-3-9 to denote weak, medium, and strong relationships are used to show the relationship (Area **D**) between customer and design requirements pairs. Similar rating scale is also used to quantify the relationship values of engineering design requirements (Area **E**). The targets (Area **F**) for each of the design requirements are also given at the bottom of Figure 3-4.



Source: Wasserman, 1993.

Figure 3-4 Example of HOQ matrix

3.5 QFD Studies

3.5.1 Pros and Cons of QFD methodology

Many authors in the literature reported the benefits of using QFD [Halbleib et al., 1993; Dean, 1992; Griffin, 1992; Ohfuji et al., 1990; Aswad, 1989 and Cohen, 1988]. The most significant benefits of QFD are the following: quantifies customer requirements; enforces a methodological analysis of the interrelationships of product characteristics and customer needs; encourages the experts to quantify their expertise and to resolve conflicting requirements using data (which might be a difficult task), promoting system optimisation rather than component sub-optimisation; provides for problem prevention by identifying design problems and manufacturing bottlenecks a priori, i.e. it facilitates earlier design changes; provides fewer problems when releasing new products, which can be attributed to the fact that the design changes are made at an earlier stage; provides lower costs when starting up the production of new products, owing to the problems being identified at an early stage; provides shorter product development times; provides fewer problems with the product on the market; facilitates information processing among various departments; and builds up knowledge, since the work is documented.

On the other hand, there are disadvantages and difficulties in conducting QFD. It is time-consuming. It is difficult to find the suitable extent and scope of a project. It is also difficult to find the appropriate design attributes that meet customer requirements.

3.5.2 Review of Related QFD Studies

In the succeeding paragraphs, selected studies on the application of quality function deployment methodology and also in particular to address environmental issue (see section 3.4) are reviewed.

Park and Kim [1998] proposed a method to determine the optimal set of design requirements by using QFD. Instead of using the conventional scheme of 1-3-9 (which is commonly used in many QFD studies) for assigning relationships ratings between customer requirements and design requirements, they used a multi-attribute decision method (a swing method) and also considered the correlation between design requirements in their mathematical formulation that is neglected in many QFD studies. They formulated a quadratic integer-programming model with consideration of cost trade-offs among design requirements. Zhou [1998] proposed in his research fuzzy ranking procedure to prioritise engineering characteristics and optimise the improvements in design and quality through a mixed integer programming. His research has taken no account of the environmental aspect and the correlation between engineering characteristics in designing a product. He applied his methodology in software industry.

Elboushi & Sherif [1997] utilised QFD as tool for effective acquisition of requirements and design analysis in software industry. They highlighted that QFD assists in focusing the effort to produce a product for customers with diverse needs and used the methodology with the support of modern object-oriented design software technology. Based on their results, they concluded that QFD process enables one to capture requirements and produce specifications that are efficient, robust, and consistent. According to them, in comparison with other classical methods, QFD were faster by a factor of 50% and more robust by a factor of 60% with respect to identification of conflicting requirements or potential bottlenecks, and more consistent by a factor of 70%. Henke [1996] explored the integration of QFD and other supporting tools in the development engineering phase in the automotive industry as well as increased use and knowledge of hypertext technology. With regard to hypertext and QFD, this would mean that different information entities like customer requirements can easily be correlated with the customer group expressing these requirements or the technical characteristics that were derived from the requirement.

Wolfe [1994] proposed to make QFD more adaptable in many organisations with the use of decision support system (DSS) and group support system (GSS) technology. He used the hypertext tools to allow the development of a low-cost DSS implementation to support QFD. Implementing QFD using hypertext allows many persons involved in the system acquisition process to attach rationales, models, histories, computer-aided design (CAD) and computer-aided manufacturing (CAM) drawings, and voices wherever useful to the QFD documents. His study made the QFD implementation computer-oriented as compared to the conventional paper–based form. Wasserman [1993] presented a simple linear cost constraint function to select the most appropriate design requirements under a limitation of a given target cost. He extended the concept of Lyman's deployment normalisation to account for dependencies that may exist between design requirements.

3.6 QFD and the Environment

Quality function deployment is found to be of much use in the business process, and in the design phase of products and processes in discrete manufacturing industries. However, there are only few studies that explore the use of QFD in environmental activities. Some of these activities in which QFD can be effectively used include regulatory compliance, emission reduction, pollution and loss prevention programs, construction or operating permit acquisitions, and equipment procurement (equipment leaks) [Berglund, 1993].

Berglund argues that the idea behind the QFD concept can assist the companies in preventing pollution at the source and can encourage breakthrough thinking of new concepts and technology that focus the environmental activities of the firm to best meet the interests of the stakeholders. In his study, he claimed that the use of QFD is also a unique challenge because the ultimate consumer only interfaces with the actual product after it has been mixed with something else, chemically changed, refined, treated, etc. But numerous stakeholders are directly or indirectly affected during all stages of the production, transport, handling, and disposal of its intermediates, by-products and wastes. The stakeholders concerned with the environmental performance of a plant, product or project include state and local regulators, the local community, the environmental community, engineering, maintenance and operating staff, equipment and raw materials suppliers and even competitors.

Moreover, Berglund made a suggestion on the applicability of QFD for environmental decision-making in process industries. However, it should be pointed out that using QFD in the environmental arena requires the inclusion of a range of new evaluation criteria associated with hazardous waste generation, waste disposal options and long-term liability requirements. Also, the definition of external customer should be broad which includes regulators, citizen groups, and suppliers as well as the immediate client.

Prior to his study in 1993, Berglund [1991] also considered the concept of ‘hidden’ or second plant. According to this concept, even in highly organised factories, this second, or hidden plant, estimated by Feigenbaum [1983] to represent 15 to 40% of all production capacity was actually dedicated to reworking unsatisfactory product, replacing product recalled from the field, or retesting and rejected batches. Describing the concept in a much broader way, in a typical production facility, the second or hidden plant is converting raw materials, not to final product but to waste. This waste can take the form of unsatisfactory product, but often in the form of emissions to air and water, or solid waste. If this is the situation, the second plant might not represent 15 to 40 % of the total production capacity, but could approach upwards of 60 to 90% of this capacity (if 2 to 10 pounds of wastes materials are generated for each pound of end product created) [Berglund, 1991]. Out of the 4 waste management options he described - direct discharge, regulatory compliance, waste management, and the pollution prevention -, he recommended that chemical process industries should start focusing more on pollution prevention before they pursue other waste management options.

In similar studies, Masui [2000] accounts the potential application of quality function deployment in considering environmental requirements at the early stage of product development such as in the case of the design of hair dryer. Like many authors, he stated that at the early phase of product design, information is scarce and hardly defined and the degrees of freedom are large. He further advised that as LCA (tool used at the end of the detailed design to evaluate environmental impacts, which is discussed in the next chapter) has been continuously investigated and developed nowadays, however, support tools to assist in the incorporation of environmental considerations at the early design have been inadequately developed. Thus, Masui has insinuated to explore the adoption of LCA method at the early stage of product development. Akao & Hayazaki [1998] carried out a research on how environmental quality can be built into the company’s environmental management system with the use of ISO 14000 and quality function deployment (QFD). Cristofari, Deshmukh, and Wang [1996] initiated the development of Green QFD (GQFD) which was further refined by Zhang et al. [1999], where LCA and QFD together with LCC are combined to evaluate different product concepts with consideration to quality requirements, environmental impact and production costs at the design stage of engine oil filters with the use of analytic hierarchy process (AHP). Hanssen et al. [1996] and Foerde et al. [1995] applied QFD, LCA, and LCC separately for environmental assessment of different products, but this has not formed a systematic methodology. Stornebel and Tammler [1995] suggested the incorporation of environmental requirements into traditional QFD without showing a concrete example on how it is possibly integrated. However, in these latter studies, they have neglected to consider the uncertainty and incompleteness of design data available at the early stage of product development.

Recently, the latest research that explores the applicability of QFD in connection to environmental aspects of process improvement was conducted by Halog, Schultmann and Rentz. [2001]. A modified version of first phase of QFD (HOQ) was developed and called "House of Ecology (HOE)" that deploys environmental requirements (in the form of environmental impact categories) instead of quality requirements for the purpose of improving the environmental performance of selected Best Available Techniques (BAT) at a given budget constraint. This HOE is shown in Figure 3-5 below.

The modifications introduced in standard QFD methodology and the defined areas in Figure 3-5 are as follows:

1. The stakeholder requirements are defined as *impact categories*, which became popular in Life Cycle Analysis (LCA). Impact categories compile the potential impacts on the environment caused by the individual emissions and consumptions and reflect environmental problems;

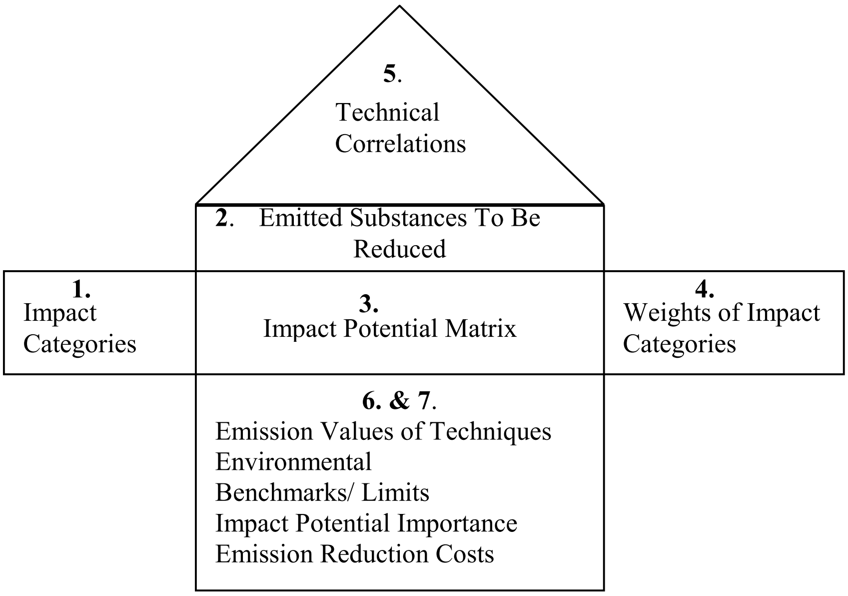
2. The design requirements of a particular technique are expressed in terms of substances that the process emitted which need to be reduced, e.g. SO_2, NO_x;

3. Instead of using the commonly used 1-3-9 equivalent of weak-medium-strong rating scale for evaluating the relationship of design requirements and stakeholder requirements, the **impact potential matrix** (relationship matrix) is described as the degree of contribution of a certain substance to a certain impact category. For example, in what degree contributes SO_2 to the acidification of the environment? The impact potential (IP) of this substance was used as measure of the degree of satisfying the requirement of less acidification and was normalised;

4. The weights of impact categories are based on environmental experts' opinions;

5. The triangular top portion of HOQ (technical correlation) was not used because the correlations of the emitted substances have not yet been explored and needed to be researched first. Most of the QFD studies left this portion due to complexity. The correlation of the emitted substances might give us a hint on possible cost savings from simultaneous implementation of reduction measures between two and more emitted substances;

6. The target specifications were the results of the environmental benchmarking of emission values for the techniques considered but alternatively, emission limits for water, air, and land as provided by environmental agencies could also be used if available;



Source: Halog et al., 2001

Figure 3-5 House of Ecology (HOE) Chart

7. The emission reduction cost is defined as the cost of implementing the necessary emission reduction plan for a particular substance to meet the current environmental benchmarks or latest limit. This cost could be attributed to new installations or equipments within the process, changing of raw materials, and changing operating conditions or parameters; and

8. The ranking of the emitted substances was based on both emission reduction cost and environmental impact potential considerations. Cost budget was allocated first to the one that had the greatest impact potential to the environment. The cost budget allocation was demonstrated by a mathematical model as shown below.

Mathematical Model for Cost-Effective Environmental Performance Improvement

An emission reduction-planning model is used to determine on how to optimally allocate the given cost budget to the various emissions to be reduced for a given technique such that effective environmental process improvement is achieved. The greater the impact potential importance of the emitted substance to the environment, the more it is environmentally critical and the greater its chance being selected and allocated with budget. The objective function is to maximise the total impact potential importance of selected emitted substances for each technique which is synonymously defined here as the degree of necessary improvements in environmental process performance of each technique. The greater the total impact potential importance of the selected emissions of a technique, the more environmentally unsafe is the technique and thus requires substantial environmental process improvement to achieve the acceptable level of emissions. On the other hand, the lesser the total impact potential importance of the selected emissions of a technique, the more environmentally safe is the technique and thus requires minimal environmental process improvement to meet the acceptable level of emissions. The total impact potential importance (Z) of a technique that varies from 0 to 1 (0 to 100%) is referred as the degree of necessary improvement for environmental process performance.

The binary-type integer programming model for maximising the sum (Z) of the impact potential importance of selected emissions by selecting appropriate substances for reduction within a given available budget or investment (*B*) for improvement, is proposed as follows [Halog et al., 2001]:

$$Z = \max\left\{IPI_1 x_1 + IPI_2 x_2 + \ldots + IPI_n x_n\right\} \qquad (1)$$

s.t.

$$c_1 x_1 + c_2 x_2 + \ldots + c_n x_n \leq B \qquad (2)$$

$$x \in \{0,1\}$$

where IPI_j is the normalised impact potential importance of an emitted substance *j*.

$$IPI_j = \sum_{i=1}^{m} w_i R_{ij}^{norm} \qquad (3)$$

$R^{norm}{}_{ij}$ is the normalised value of impact category *i (i=1,2, ...,m)* and substance *j (j=1,2,..n)* in the impact potential matrix (Area 3) of Figure 3-5 and w_i is the weight of impact category based from expert's opinion. The decision variable, x_j, is binary (i.e., if substance *j* is selected, $x_j=1$. Otherwise, it is 0). The cost coefficients $c_1, c_2, \ldots, c_n$, represent the estimated costs for reducing the said emissions to the desired emission benchmark. Presently, it is assumed that when a particular emitted substance is selected with its corresponding cost, the desired emission limit is achieved after the necessary solution has been made. The cost for reduction is assumed to be constant with respect to percentage of emission reduction. The problem is solved using the well-known 'Knapsack' problem approach.

3.7 Brief Chapter Conclusion

QFD helps to introduce the idea of quality in the early phases of the requirements cycle and to re-evaluate quality considerations throughout the project's entire life cycle. It promotes system optimisation rather than component sub-optimisation. QFD assigns priority to product improvements and reduces development time by minimising changes and concentrating on defect prevention rather than defect detection. This methodology also results to fewer problems when releasing new products, which can be attributed to the fact that the design changes are made at an earlier stage. Its use facilitates the process of concurrent or simultaneous engineering and integrated product development.

Other than quality consideration at the early design stage of a product system, the present study will consider the environmental aspects, which is disregarded in most QFD studies conducted. The House of Ecology (HOE) explained above will be further modified and adapted in the development of conceptual methodology, which is discussed in Chapter 7. Angell et al. [1999] suggested that environment should be included on an equal basis with current concerns about cost, quality, service, and flexibility. Environmental requirements must be integrated with management's efforts to address the needs and concerns of all stakeholders, a challenge that in the past has received little research attention.

The next two succeeding chapters will tackle the influences of environment and cost at the conceptual phase of product development.

4 Environmental Consideration and its Related Concepts

Other than quality aspect, environmental performance of products and processes is a major concern of industrial firms particularly in this decade. The greening behaviour of many manufacturing companies is a result of a consumer demand for environmentally friendly products, legislative reforms, and enhanced awareness of the importance of common environmental resources. In this chapter, it is shown how environmental performance becomes an important parameter in the design of products and how environmental management relates to the over-all concept of total quality management (TQM). Also, different environmental related concepts such as design for sustainability, life cycle assessment and design for environment are discussed.

4.1 Relationship of Environmental Management and Quality Management

Total quality management in operations management provides a striking parallel with environmental management [Klassen & Mclaughlin, 1993]. Like quality, a long-term goal of environmental management is to move toward the proactive stance, considering environmental aspects in an integrated fashion in product design, the entire manufacturing process, marketing, product delivery and use, customer service, and post-consumer product disposition [Hunt and Auster, 1990]. Living up to the total quality designation, this is best achieved by the inclusion of the environmental dimension. The convergence of these two fundamental thrusts, one based on environmental stewardship and the other based on the total quality management (TQM) movement resulted to a practice called total quality environmental management (TQEM). TQEM is defined as the identification, assessment, and continuous improvement of environmental attributes that contribute to the total quality of a company's products and operations [Fiksel, 1996, p. 41; Paton, 1993]. This more rigorous definition of quality will mean that it has not only to satisfy such traditional consumer demands such as greater durability, user- and maintenance friendly, higher satisfaction value, and employee demands such as joint influence and development and commitment, but that it must also take place under forms which, neither during a product's manufacture nor when it is ultimately discarded, will have a detrimental effect on the natural environment [Ulhoi, 1995].

Thereby, in choosing an alternative that has the least environmental impact, designers and managers are faced with constraints such as cost, product quality, material supply, production schedules, etc. as well. Alternatives, which are beneficial to the environment but neither cost-effective nor profitable for the company, are not viable and sustainable solutions. Thus, it is important to incorporate every operating constraint into the initial design phase of the product or process life cycle [Matysiak, 1993]. As pointed out in the previous chapters, it is found that although the design phase of the product realisation process accounts for only 5% of the product’s total cost, between 70 and 80% of the product’s life-cycle cost (materials, manufacturing, distribution, servicing) are actually determined by its design [Oakley, 1993]. Where environmental concern is becoming a parameter of growing importance in a global market context, it is critical that production managers are able to assess the overall importance impact of production activities.

Because of this realisation towards the importance of ecological issue, both governments and leading global manufacturers compete to demonstrate their environmental credentials. Manufacturers are nowadays considering how they may improve the environmental performance of their products at the initial stage. Governments are considering which product policies should be promoted to effect environmental improvement. Consumers are asking for products that do less environmental damage to their communities and their world. Competitors are seizing on environmental characteristics of products as a means to gain competitive advantage.

4.2 Environment-oriented Marketing

The environmental drivers that drive companies to improve their environmental performance are regulatory requirements; cost and liability reduction such as pollution control equipment; fines for non-compliance; environmental liability insurance; strategic and competitive such as ISO 14000, EU Eco-Management and Audit Scheme (EMAS) and EU Eco-labels; and social/community issues such as community relations, plant siting problems, and right-to-know requirements [Veroutis et al., 1996]. Due to the pressures from consumers, governments, communities and other stakeholders, manufacturers have become more aware of the environmental implications of their operations [Gupta et al., 1996; Sarkis, 1995]. Producers have taken into account for the environmental consequences of their products. Company-level consumer policy is evidenced by the development of products on the basis of consumers’ wants and desires. Some key customer requirements emerging from market pressures are as follows: make packaging reusable or recyclable; prevent adverse health effects from using product; provide reuse/recycling programs for batteries, cartridges, and other consumables; provide information on material content and materials used in manufacturing; use energy and materials efficiently; provide upgrade paths that minimise disposal of existing products; and collect and reuse or recycle products after their useful life.

Antonides et al. [1998, p. 509] conducted a survey on the degree of environmental awareness of consumers. They found out that the general environmental concern had been high and yearly increasing in Western and Eastern Europe particularly in Germany and Scandinavian countries. Many consumers are becoming environmentally responsible when making decisions concerning products. Consumers who demanded a minimum level of environment-friendliness may exclude products harmful to the environment from their consideration sets. Ulhoi [1996] reported that there is a growing trend among ordinary customers to demand more recycling and energy efficiency and to adopt environmental criteria in their purchasing decisions. For example, consumers may choose between alkaline paint on oil basis and acrylic paint on water basis. Roenning, Hanssen and Moeller [1993] reported the life cycle assessment of these two paint product types. By using alkaline paint, volatile substances are emitted, which are harmful to the environment. Acrylic paint is less harmful to the environment but it is more expensive and requires some changes in the manner of painting. Acrylic paint dries relatively quickly during warm weather. Moreover, according to Rentz et al. [1999a, p.776), for the last few years, the ratio of sales to water-based to solvent-based paints has strongly increased. The reasons for this are due to several factors: performance of water-based paints has been considerably improved over the past years, and handling characteristics have become easier, e.g. low odour, clean-up with soap and water. However, some problems do remain: final appearance of water-based paints does still not give entire satisfaction; furthermore, in some application fields such as interior decorative specialties and particularly wood coatings, water-based products do not match solvent-based paints. Rentz et al. further reported that most of the research on water-based product development is focused on improving the properties of water-based products, which are still inferior to the corresponding solvent-based products, such as high gloss enamels, varnishes, wood stains and finishes, and floor finishes. Furthermore, other consumers have to trade-off environment-friendliness against other attributes such as price and quality performance. For instance, consumers have to trade-off the environmental benefits against the higher price and the need to paint in a different way, particularly when water-based paints are used.

In addition to incorporating environmental aspect into the design of products, some firms have also used the environmental friendly characteristics as differential competitive advantages in the marketing of their products, for example, products of the Body Shop. Such advantages could be in the form of more favourable pulibc perceptions, increased market share and cost savings.

4.3 Pollution Prevention

According to the EPA's official definition [Habicht II, 1992], *pollution prevention* means "source reduction" as defined in the Pollution Prevention Act, but also includes "other practices that reduce or eliminate the creation of pollutants through (1) increased efficiency in the use of raw materials, energy, water, or other resources, or (2) protection of natural resources by conservation." Pollution prevention can best be achieved by preventing pollution and waste from being created at the very beginning of the design process or at the design stage [Bloemhof-Ruwaard, Koudijs & Vis, 1995; Overby, 1991; Hunt et al., 1990; Dougherty, 1990]. Wilhelm et al. [1993] reported that pollution prevention has increasingly come to be viewed as a better approach to reducing both hazardous and non-hazardous wastes before they are generated rather than treating and disposing of them afterward. For instance, Germany aims at favouring pollution prevention in the environmental licensing procedure [Rentz, Hähre and Schultmann, 1999, p. 195]. In Germany, the legislation laying down measures towards "avoidance, utilization and disposal" of waste is set down in the Federal Recycling and Waste Management Act (Kreilaufwirtschafts-und Abfallgesetz) [KrW-/AbfG, 1994, p.2705], which came into force in October 1996 and is the most important part of the new GVVM (Gesetz zur Vermeidung, Verwertung und Beseitigung von Abfällen). This Act has three main principles: production and consumption must be organised in such a way as to prevent waste from the very beginning; unavoidable waste must be recovered using high-quality techniques; and non-recoverable waste must be properly disposed. It is also stated in this German Act that prevention and recovery of waste have priority over its disposal [Spengler et al., 1997; Penkuhn et al., 1997]. Furthermore, this legislation also broadens the entire national waste concept and sets new priorities with regard to the avoidance and the duty to utilise waste such as making differentiation between waste "for recovery" and waste "for disposal". As a result of this legislation, the regulations that had been binding for packaging since 1991 became valid for all consumer goods and commodities. Anyone producing or processing of goods bears the product responsibility for them. It is up to the manufacturers to bear ecological responsibility for their products, especially after use [Matten, 1996]. The Product Recycling and Waste Management Act provides a few examples. These are:

- Products should have a long service life and be suitable for multiple uses;
- Recoverable waste or secondary raw materials should be used for production; and
- Used products should be taken back and removed.

In addition, a working group of the German federal states on waste (Länderarbeitsgemeinschaft Abfall, LAGA) issued a categorisation of waste types, comprising 589 types of waste, of which 333 have priority for control [LAGA, 1996] This catalogue is now replaced by the European waste catalogue (EWC) [Malorny, 1997]. According to this categorisation, for instance, in the case of zinc and lead production industry, the following types of waste may arise: slags from non-ferrous metal melting; plant residues (runner breaks, ladle breaks, converter breaks); sludges from non-ferrous metallurgy; and filter dust [Rentz et al., 1999b].

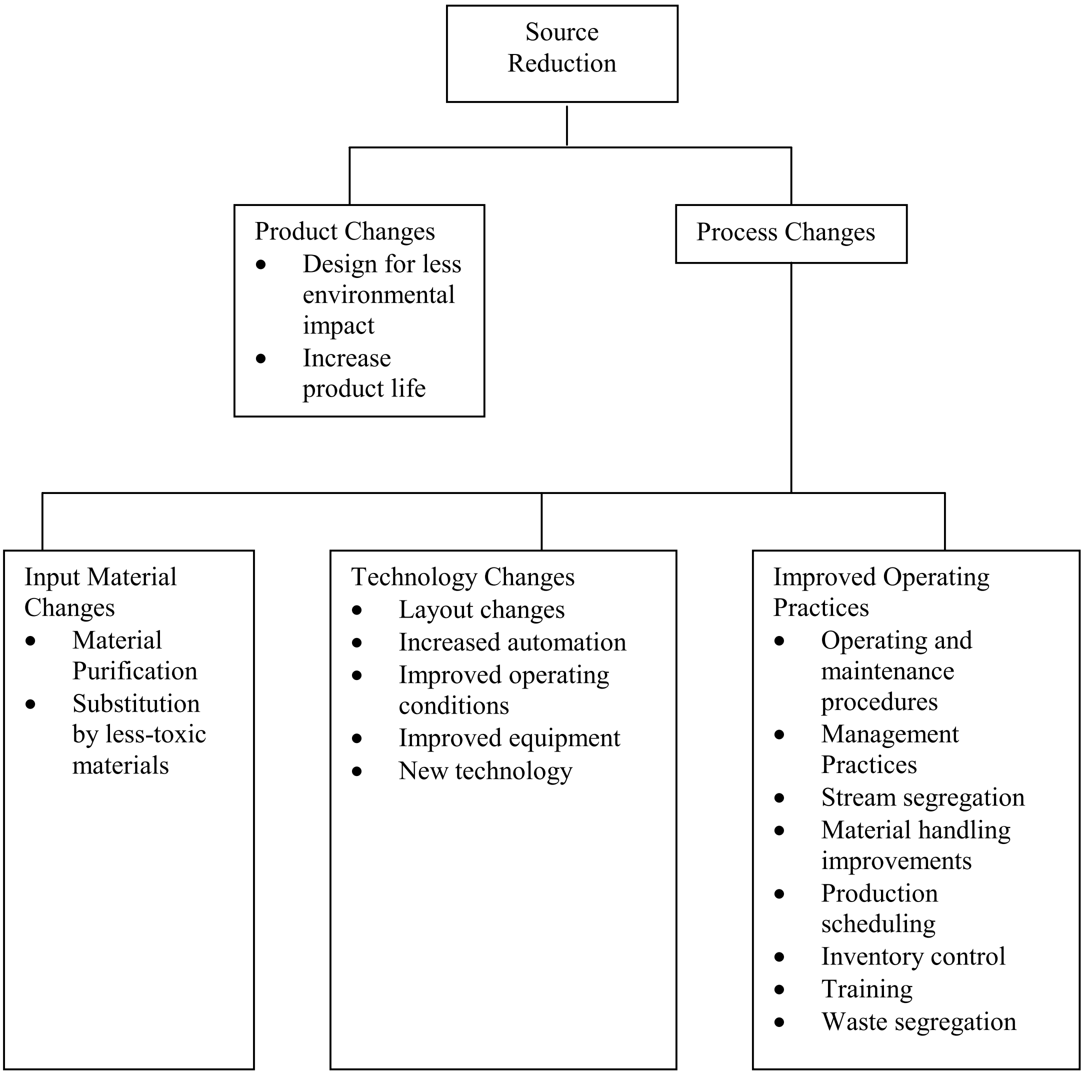
Moreover, two of the pollution prevention technologies that are currently being pursued by industries are waste minimisation technology and clean technology. Waste minimisation includes source reduction and environmentally sound recycling. Clean technology uses less raw materials, energy and water. It generates less or no waste (gas, liquid, and solid) and recycles waste as useful materials in a closed system. The clean technology used in pollution prevention can be categorised into five groups: improved plant operations, in-process recycling, process modification, materials and product substitutions, and material separations.

Successful pollution prevention demands attention to 8 aspects of a manufacturing operation: (1) product design, (2) process design, (3) plant configuration, (4) information and control systems, (5) human resources, (6) research and development, (7) supplier's role and relationship, and (8) organisation. As firms invest in new environmental technologies, possibly through product design and waste reduction or process redesign, emissions of pollutants to the environment can be expected to fall. Similarly, investments in management systems aimed at preventing unplanned emissions to the environment can be expected to minimise the value of compliance penalties from government agencies. Improved product design, better process selection, and easy disposal of products when their useful life ends can result in measurable and improved marketability as claimed by Feltes & Fink [1996].

Furthermore, source reduction is one of the pollution prevention methods. *Source reduction* is defined as any practice which reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. Figure 4-1 cites some examples of source reduction methods. Source reduction has also an economic advantage, since it reduces or eliminates the burden upon the later steps of the technology, such as waste treatment. Two typical methods of source reduction strategies are product changes and process changes. Product changes in the composition or use of the intermediate or end products are performed by the manufacturer with the purpose of reducing waste from manufacture, use, or ultimate disposal of the products. Process changes, on the other hand, are concerned with how the product is made. These two methods of source reduction enable the volume and toxicity of production wastes and end products to decrease during their lifecycles and at disposal. Also these changes reduce worker exposure to pollutants during the manufacturing process. Typically, improved operating practices can be implemented more quickly and at less expense than input material and technology changes.

4.4 Cleaner Production

Cleaner production, as defined by United Nations Environment Programme (UNEP), is the conceptual and procedural approach to production that demands all phases of the life cycle of a product or of a process should be addressed with the objective of prevention or minimisation of short and long-term risks to humans and to the environment. A total societal commitment is required for effecting this comprehensive approach to achieving the goal of sustainable societies [Rydberg, 1996, p.387]. It is one of the four subprogrammes of the UNIDO environment programme since 1990, and it was endorsed by UNIDO Member States in the recommendations of the UNIDO Conference on Ecologically Sustainable Industrial Development (ESID) in October 1992 [UNIDO, 1992]. Cleaner production technologies



Source: Freeman, Puskas & Olbina, 1995, p. 423

Figure 4-1 Source Reduction Methods

concentrate at the minimisation of the generation of wastes and emissions rather than their elimination when they are produced. It is one of the fundamental strategies within a sustainable industrial development. Cleaner production means that the best technology available is applied for product modifications, changes in process operation and technology, and changes in raw and input materials.

Baas and Huisingh [1993] analysed that they were three major shifts in the development of environmental technologies towards cleaner production. These are:

1. From pollution control and waste handling technology after pollutant generation , to proactive, process integrated technology, that prevents the generation of pollutants at their sources;

2. From a sole emphasis upon technological measures to a broader perspective which also encompasses non-technical measures:

3. From consideration of only the environmental aspects of the manufacturing process, to consideration of the environmental aspects of the entire life-cycle of products, including product design, sustainable resource management, consumption and post-consumer management of used products.

Table 4- 1 elaborates the different elements involved in this development. It is clear that for the well-being of mankind, a development of sustainable societies is needed. Cleaner production is fostering this integrated approach, economically and ecologically sound approach that is equally applicable in production and service orgaisations. The cleaner production approach can stimulate the integration of environmental factors as part of a sound strategic management plan, and can be the basic foundation for sustainable corporate operations [Dielemann and Baas, 1991].

Table 4-1 Development of Environmental Technology Concepts

	Best Available Technology/Best Practicable Technology	Clean(er) Technology	Pollution Prevention & Waste Reduction	Clenaer Production
Pollution control	**X**			
Prevention		**X**	**X**	**X**
Technological	**X**	**X**	**X**	**X**
Non-technical			**X**	**X**
Process-oriented		**X**	**X**	**X**
Product-oriented			**X**	**X**
Strategic Management				**X**
Society-oriented				**X**

Source: Baas, 1997, p.216.

“Clean Production” also stresses the vision of reaching a goal where antropogenic activities are compatible with ecosystems. This goal would then be essentially the same as that of sustainable development. As stated by Jackson [1993], sustainable development includes production processes, product cycles and consumption patterns which allow for human development, and the provision of basic needs without degrading and disrupting the ecosystems within which that development must occur.

In the philosophy of cleaner production, switching from waste treatment to waste minimisation requires technological changes in the chemical process industries. Technological changes can be categorised into two areas: retrofitting on existing industrial activities and development of new cleaner processes. Heuristically, incorporating waste minimisation during process design is less complicated than modifying the manufacturing process itself at an existing plant. One of the significant consequences of pollution prevention is that it is often an economical approach. When wastes are reduced or eliminated, cost savings in materials result and more products are produced from the same starting materials. The close examination of manufacturing processes needed to plan a successful pollution prevention approach can produce a number of side-benefits as well, such as significant improvements in energy and water conservation, and improved or more consistent product quality [Freeman et al., 1995, pp. 420-421; Freeman, 1990, p. 343]. The environmental advantages of pollution prevention approaches include effectiveness, minimising uncertainty, avoiding cross-media transfers, and protecting resources. As opposed to the traditional "end of pipe" treatment for pollution control, pollution prevention is a "front end" approach. End-of-pipe techniques refer to technologies that address the problems once they are already produced and are not preventive at all such as best available techniques (BAT) and best practical techniques (BPT). Hence, in order to be maximally effective, pollution prevention must be incorporated into every aspect of manufacturing, including product and process research, plant and process design, plant location and other planning aspects, and the steady state production process [USEPA, 1988]. In a related research, Fichtner, Frank & Rentz [2001] explore the concepts of inter-firm energy supply as an option to achieve cleaner energy production because materials and energy do not leave the economic process and they further applied their proposed concepts and methodology to the network of Karlsruher Rheinhafen. Additionally, Spengler et al. [1998] cautioned that the planning of new products or cleaner production processes should not only require strategic alignment, but also a sound evaluation for reliable decisions where the principles of engineering, accounting and strategic management have to be taken into account.

Importance of Cleaner Production

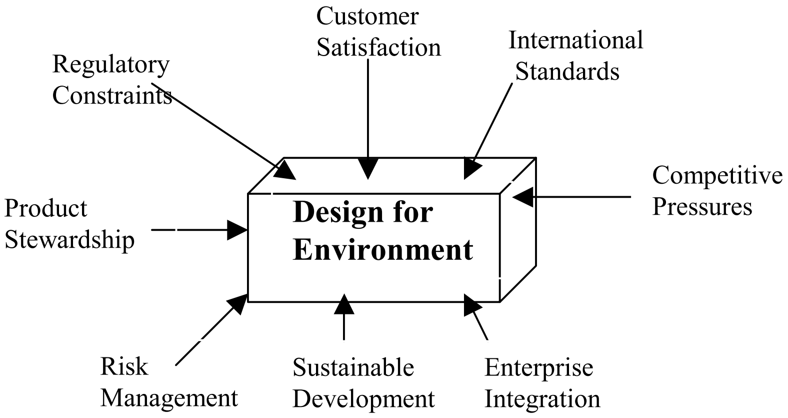
Cleaner production requires the continuous application of an integrated preventive environmental strategy to processes and products to reduce risks to humans and the environment. The key issue is how to improve the efficiency of industrial production, by reducing wastes and redesigning products to make them less polluting and easier to recycle. The need is particularly great in small and medium size enterprises. The needs for action are three-fold [Luken, 1996, p.280]:

- Creation of government policies that encourage environmental management with an emphasis on pollution prevention as the first step in reducing the generation of wastes;
- Support for institutions that can effectively implement cleaner production programmes based on process optimisation;

- Demostration projects that show that the environmental and financial benefits of cleaner production are as applicable to small and medium size enterprises in developing as in developed countries.

4.5 Design for Environment

Industrial ecology is an approach to industrial design that examines the entire product or process life cycle design in concert with surrounding industrial systems, such as design for environment. Design for Environment (DFE) is defined by Lenox, Jordan, and Ehrenfeld [1996] as the systematic process by which firms design products and processes in an environmentally conscious way. Another definition of DFE provided by Fiksel and Wapman [1994] is "the systematic consideration during new production and process development of design issues associated with environmental safety and health over the full product life cycle." The goal of DFE is to place environmental and health consideration on an equal basis with traditional cost, quality and performance criteria [Steele and Allen, 1998 & 1996; Steele, 1995; Johnson and Gay, 1995]. Additionally, Horvath et al. [1995] provided three goals of DFE, which include (1) minimising the use of non-renewable resources, (2) effectively managing renewable resources, and (3) minimising releases to the environment. The scope of DFE encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention, and waste management. Figure 4-2 shows the driving forces that influence the adoption of design for environment (DFE) by corporations [Fiksel, 1996, pp. 20-21].



Source: Fiksel, 1996, p. 20.

Figure 4-2 Driving Forces influencing adoption of DFE

Moreover, DFE is poised to start the process of continuous environmental performance improvement. Design for environment analysis can be applied to products and processes to integrate environmental considerations into engineering design processes. The most overwhelming motivation of the company to integrate environmental parameter in the product and process design is the availability of corporate environmental policy [Hunkeler and

Vanakari, 2000]. Other important reasons for incorporating environmental parameters in the design process are presented in Table 4-2.

Table 4-2 Designers' reasons for incorporating environmental parameters in design

Reasons for incorporation	Percentage of designers responding positively (%)
Firm has an environmental policy	81
Firm has an EMS	48
Firm uses LCA	48
Customer Pressure	48
Marketing	48
Comparison with product group	48
Current or pending legislation	44
Community group pressure	22
Non-government officials (NGO) pressure	15
Supply chain pressure	15

Source: Hunkeler et al., 2000

Several DFE practices in industry today were discussed in Fiksel [1996, p. 56]. These practices include material substitution, waste resource reduction, substance use reduction, energy use reduction, life extension, design for separability and disassembly, design for recyclability, design for disposability, design for remanufacture, and design for energy recovery. Moreover, DFE required the co-ordination of several design and databased activities such as environmental impact metrics, data and database management, and design optimisation (including cost assessments) [Mizuki et al., 1996 and Eagan and Hawk, 1995]. Environmental metric is defined by Veroutis et al. [1996] as an algorithmic interpretation of level of performance within an environmental criterion. The environmental criterion is the environmental attribute of the product (that is, the energy to heat water for a specific function, grams of CO_2 produced to deliver the above energy, chemical oxygen demand generated in the wastewater, degree of risk of exposure to a toxic substance, and so on). Most of these environmental criteria can be translated into metrics and can be used to assist decision-making when the product is developed.

The methods used in DFE include life cycle analysis; qualitative approach that uses a checklist (that is, material selection and supplier selection criteria) and qualitative metrics; process and component selection optimisation techniques. Lifecycle assessment (LCA) is a process to evaluate the types and quantities of product input (that is, energy, raw material, water) and outputs (atmospheric emissions, solid and waterborne wastes, and end-of-life products). Impact analysis (IA) uses conventional risk analysis (that is, risk identification, assessment, evaluation, management, and communication) and the scoring or indexing method. Environmental impact assessment (EIA) is generally defined as a process or predicting and evaluating the impact of an action on the environment [Jain, Urban and Stacey, 1972; Therivel et al., 1992]. EIAs involve an anaylsis of the environmental characteristics of all proposed actions and possible alternatives. Furthermore, they include an assessment and prediction of future environmental conditions with or without a given action and a consideration of methods and/or techniques for eliminating or reducing any environmentally harmful effects. The end-result of an EIA is an environmental statement on the above-mentioned issues. Finally, it is decided that the proposed actions should proceed, it also includes the monitoring of the actual impacts of the proposal.

Moreover, the environmental accounting method includes activity based costing (ABC) and cost-benefit analysis and even life cycle costing (LCC), which is discussed in the next chapter, can be adapted. Bras and Emblemsvag [1995] proposed an ABC system to perform different lifecycle of processes or products. In this system, costs are traced from activities to products based on each product's consumption of such activities. Traditional cost systems assume that each unit of a given product consumes resources, while ABC systems assume that products or services do not directly use up resources but instead consume activities. Thus, for ABC systems, the cost of all activities must be considered. On the other hand, Graedel [1998] and Johnson et al. [1995] developed a practical and customer-oriented design for environment (DFE) methodology, which is a five by five matrix of life cycle stages versus the environmental, health and safety requirements for product development.

4.5.1 Environmentally Conscious Design and Manufacturing

Environmentally conscious design and manufacturing (ECDM) is a view of manufacturing that includes the social and technological aspects of the design, synthesis, processing, and use of products in continuous or discrete manufacturing industries [Zhang, Kuo and Lu, 1997; Sarkis, Nehman & Priest, 1996]. Environmentally conscious technologies and design practices allow manufacturers to minimise waste and to turn waste into a profitable product. The benefits of ECDM include safer and cleaner factories, improved product quality at lower cost, better public image, and higher productivity.

Like the previous concepts described above, the concept of ECDM encourages that pollution control must be incorporated into every aspect of manufacturing to effectively protect the environment. As opposed to the traditional "end-of-pipe" treatment for pollution control, ECDM is a proactive approach to minimise the products environmental impact during its design and manufacturing, and thus to increase the product's competitiveness in the environmentally conscious market place. The two approaches to ECDM are zero-wasted lifecyle and incremental waste control lifecycle. In the first approach, it is assumed that the environmental impact of a product during its lifecycle can be reduced to zero. The cycle can be absolutely sustainable, and the product may be designed, manufactured, used, and disposed of without affecting the environment. The emphasis in this approach is to create a product cycle that is as sustainable as possible. The second approach is based on the premise that there is a certain amount of negative impact from the current process cycle. This impact can be reduced or cleaned based on some improvement in technology that is named as incremental waste lifecycle control. This approach is to reduce the negative impact of hazardous materials through clean technology.

Current research in ECDM can be categorised into two areas, namely, environmentally conscious product design and environmentally conscious process design (also called environmentally conscious manufacturing (ECM)). The principle of ECM is to adopt those processes that reduce the harmful environmental impacts of manufacturing, including minimisation of hazardous waste and emissions, reduction of energy consumption, improvement of materials utilisation efficiency, and enhancement of operational safety [Horvath et al., 1995; Birkhofer & Schott, 1995]. The American Sandia National Laboratories' environmentally conscious manufacturing department describes ECM as "the deliberate attempt to reduce ecological impacts of industrial activity without sacrificing quality, cost, reliability, performance, or energy utilisation efficiency. The activities of ECM emphasise largely extracting the useful product from raw materials, avoiding of waste generation at the source, or using waste to create other products. In addition, ECM involves refining operating procedures, replacing existing processes and developing new, waste-free processes, finding innovative ways to redesign products, and increase recycling.

4.5.2 Green Product Design

The concept of green product design (GPD) evolves from pollution prevention. Green products are ones that can reduce the burden on the environment during use and disposal and have additional marketing appeal. Green product design refers to green engineering design, defined by Navinchandran [1993] as the study of and an approach to product and process evaluation and design for environmental compatibility that does not compromise products' quality or function. This approach is comprised of two parts: (1) the evaluation of designs to assess their environmental compatibility and (2) the relationship between design decisions and the green indicators. The aim of green engineering design is to develop an understanding of how design decisions affect product's environmental compatibility. Navinchandran further stressed the need for green design for the following reasons: (1) environmental legislation, (2) corporate image and public reception, (3) demanding consumers, and (4) rising waste disposal costs.

Moreover, Feltes et al. [1996] advised that as firms began to recognise the importance of designing products and processes to ensure quality, they could also design products and processes to reduce or eliminate their negative impact on the environment. In their work, they claimed that companies could adopt an approach similar to "off-line" quality control for pollution abatement. Off-line quality control refers to an approach that involves the improvement of product quality throughout the design process. This is a concept that is similarly called Taguchi (Quality) loss function. Taguchi defines quality as “the minimum loss imparted to society from the time the product is shipped, other than any losses caused by its intrinsic functions” [Sudhakar, 1995; Taguchi & Clausing, 1990]. Here, by designing a product that is less sensitive to variations in the manufacturing process, firms can produce a higher quality product at a lower cost. Similarly, products and processes could also be designed to prevent pollution, rather than address the wastes and pollution emissions after production. A concept of ecological loss function, which is adapted from Taguchi function, used for environmental evaluation and design of techniques was explored by Halog et al. [2000]. Ecological loss function relates money losses to the environmental attributes of a system. Environmental problems such as air and water pollution, emissions and solid wastes are defined as “Loss of/to society”. Based on calculated losses, techniques can be ranked and the best available one/s can be determined.

4.5.3 Design for Sustainability

Sustainable development, as defined in the Brundtland Report, means development that meets the needs of the present generation without compromising the needs of future generations [Enquete, 1997, p.14; Fiksel, 1996, p.4]. The challenge associated with the principle of sustainable development is to pay equal attention to ecological, economic and social objectives. These three objectives were also referred by the 12th German Bundestag’s Enquete Commission on the “Protection of Humanity and the Environment” as being the key elements of the model of sustainable development. The Commission also feels that a potential and useful way to reconcile ecological aspects of socio-economic benefits is to combine technology-push with demand-pull innovation strategies by establishing links between the designers, manufacturers, users and disposers of materials along the entire product line, and also to establish links between these groups and scientists who deal with life-cycle analyses [Enquete, 1997, p.56]. Sustainable development can be achieved only by a process of change encompassing not only technological but also societal and social innovations [Enquete, 1997, p.9; Enquete, 1995, p.16]. Thereby, one of the recommendations of the Commission to successfully implement the model of sustainable development is to develop strategies to promote the development of new processes, products and structures which conserve and do not generate harmful substances.

Design for sustainability can be considered as one of those strategies for developing new products and processes that prevent the generation of harmful environmental emissions. This industrial thrust to achieve sustainable development is also in agreement with the promotion of innovations, which is a particularly important element of a sustainable development strategy [Enquete, 1997, p.54]. Design for sustainability should be thought of as a decision-making process that aims at achieving maximum benefits while trying to minimise the use of resources, by integrating all economic, social and ecological concerns [Ling, 1996 & 1998]. This concept has evolved from pollution control to address the environmental problems before and then it advanced to pollution prevention and then progressed to design for environment. Design for environment, as mentioned above, is a process involving all environmental constraints and opportunities and producing no damage, or minimum damage, to the environment as the design objective. Design for environment, which is the intermediate step on the path to design for sustainability, uses life cycle analysis to help eliminate or reduce adverse environmental impacts as part of the design process for the entire manufacturing cycle, from raw materials selection to products in use and final disposal of these products. Although knowledge and experience about pollution control and prevention has been gained in the last four decades, there is still no complete information about the issue of sustainable development. Hence, one has to act on the basis of incomplete information. Thus, industries must develop and implement manufacturing processes, new products, and services that are congruent with the principle of Design for Sustainability. New and innovative technologies are especially vital to the practice of design for sustainability. Agenda 21 [Ling, 1998; Enquete, 1997, p.18], which was produced from Rio Conference in June 1992, positioned sustainable production and consumption as important elements in any scenario for sustainable development.

4.6 Life-Cycle Engineering and Paradigm “E”

Life-cycle engineering (LCE) may also be referred to as lifecycle design (LCD). An outstanding review and analysis of lifecycle design that supports design from an environmental point of view was provided by Alting [1993]. Lifecycle design is based on the early product concept, including product and market research, design phases, manufacturing process, qualification, reliability, customer service, maintainability, and supportability issues. Boothrod and Alting [1992] & Jovane et al. [1993] distinguished six phases in the product lifecycle such as need recognition, design development, production, distribution, use, and disposal. All of the phases must be considered in the conceptual stage, where it is possible to inexpensively change a solution to accommodate the requirements in each phase and in the total lifecycle. In contrast, Züst et al. [1992a and 1992b] reported four phases of the product lifecycle: (1) product definition, (2) product development, (3) product manufacturing and marketing, and (4) product usage. At each of these phases there exists a definition of objectives, activities, and deliverables for the next phase. They described that during the conceptual model phase, various designs and simulation models of the products are generated. From these conceptual models, requirements, specifications, and analyses will evolve decisions for breadboard and brassbound models.

Recently, there is a new paradigm of manufacturing called Paradigm ‘E’. According to this new paradigm, the life cycle design of products, processes and systems as well as environmental stewardship became a matter of competitive strategy in the global competitive market place. Adopting the ‘Paradigm E’ means accepting that ecology, environment, energy, economy, empowering and excellence matter to organisations and to their customers. Clearly, the challenge of the Paradigm ‘E’ is not only to chart an effective competitive strategy, but also to provide environmental stewardship. Environmental stewardship involves (1) putting protection of the environment above parochial competitive gains, (2) curtailing urges to stimulate customer ‘wants’ of the ‘throw-away’ consumerism, and (3) sharing environmentally safe technologies for improvement and protection of the environment [Molina et al., 1998, p. 430].

4.7 Life Cycle Assessment

The present study is focused on products and not on processes. Products are regarded as carriers of pollution or bearers of environmental burdens [Frankl et al., 1999, p. 1; Alting et al., 1998; Brunn et al., 1997]. They are not only a potential source of pollution and waste during their use but can also be a cause of resource depletion, energy consumption, and emissions during their life starting with the extraction of the raw materials and ending with their disposal.

Environmental performance of a product is evaluated throughout its life cycle, by using the life cycle assessment method. Lifecycle assessment (LCA) is a method for assessing materials, services, products, processes and technologies over the entire product life. The basic objective of LCA is to guide decision makers, whether consumers, industrialists, or government policymakers, in devising or selecting actions that will serve to minimise the environmental impacts while furthering other objectives. Thus, this tool must act in concert with traditional motives for selecting one action over another, including economic, engineering, and social goals [Field III, Isaacs & Clark, 1993]. LCA is a systematic approach used to manage the environmental impacts of products and service systems. It is applied at several levels: (1) conceptually as a thought process that guides the selection of options for design and improvement, (2) methodologically as a way to build a quantitative/qualitative inventory of environmental burdens or releases, to evaluate the impacts of those burdens or releases, and to identify alternatives to improve environmental performance. Formally, the ISO-standard definition of lifecycle assessment is as follows:

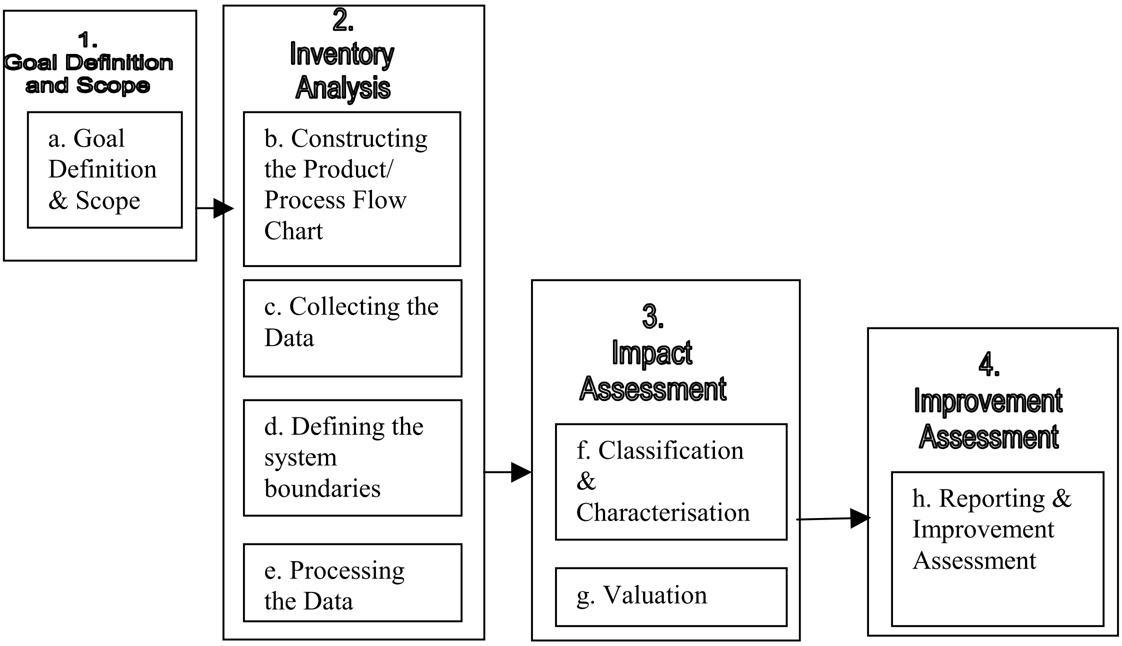
“LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by:

- *compiling an inventory of relevant inputs and outputs of a product system;*

- *evaluating the potential environmental impacts associated with those inputs and outputs;*
- *interpreting the results of the inventory analysis and impact assessment phases in relations to the objectives of the study."* [ISO 1996, p.iii]

Lifecycle assessment is divided into four main stages [Consoli et al., 1993; USEPA, 1993; SETAC, 1991]. The framework of LCA is shown in Figure 4-3 and the stages include:

1. *Goal and scope definition* defines the goals of the LCA study, the functional unit of the product system and sets the boundaries of the investigation. The functional unit of the product system is an important element in the LCA model and has to be defined clearly and quantitatively. The four elements that have to be considered in defining the right functional unit for a product system are the efficiency of the product in fulfilling some well defined user requirements (e.g. kg of paint necessary to cover 100 m^2 of platform surface); the life span of the product (e.g. how many times and to what degree do we need to repaint a surface of 100 m^2 during 25 years with different products); the fulfilment of user requirements to a certain standard (e.g. that the anti-corroding properties of paint should reach a given standard); and the fulfilment of different types of functions by one and the same product (e.g. a paint product should for instance both have anti-corroding function and a light reflecting function; a refrigerator will both keep the food cold, and produce heat).



Source: Zhang et al., 1999; Schaltegger et al., 1996.

Figure 4-3 The LCA Framework

2. *Inventory analysis* quantifies the consumption of resources (including energy carriers), the wastes generated, and the emissions to the environment associated with the whole life cycle of a product or process, from the extraction of the raw materials (cradle) to the final disposal (grave). It basically describes material and energy flows. The life cycle can be described as a system of connected activities, either processes or transports. In a quantitative LCA, the relations between the components of the system are described mathematically. Environmental impacts are described as effects caused by all energy and material flows, from the environment to the components of the product system and from the components of the product system to the environment. These flows are known as "elementary flows" [Henintz and Baisnee, 1992] and they are defined as flows passing the borderline, beyond which they are no longer controlled by human activities (antropogenic processes). The inventory analysis consists of the following parts: defining the product system, i.e, identification of material flos and processes required and relevant for the production, use and dispoisal of the functional unit for all alternatives to be compared; collection of data of energy inputs into and emissions out of all components of the product system; and calculation of energy inputs into and emissions out of all components, account being taken of the flow through each component.

3. *Impact analysis* relates the outputs of a system to their impacts on the external world. In classification, the inputs and outputs identified in the inventory analysis are assigned to the respective impact categories. The 'impact potential' is then modelled by multiplying the amount of consumption or emission with the respective impact assessment factors. It must be noted that the linear impact assessment factors are not designed for a realistic modelling of complex interdependencies and toxicological issues but only for a rough estimation of the potential environmental damage without further consideration of local impacts or dose response. Thus, one of the most critical characteristics of the impact assessment phase is the inherent subjectivity [Cristofari et al., 1996]. Due to the complexity of the interdependencies of the ecological effects caused by the different substances, any environmental assessment can allow only a simplified representation of the current situation by stressing individual problems.

Currently, the following environmental impact categories within the 3 main categories of resource depletion, health impacts and ecological impacts are being discussed:

1. Consumption of resources (including energy) [Heijungs et al., 1992; Rentz et al., 1998; Schmitz, Oels, Tiedemann, 1995]

2. Global Warming [Heijungs et al., 1992; Schmitz et al., 1995]

3. Ozone Depletion (stratosphere) [Heijungs et al., 1992; Schmitz et al., 1995]

4. Humantoxicity [Heijungs et al., 1992; Rentz et al., 1998; Schmitz et al., 1995]
5. Ecotoxicity [Heijungs et al., 1992; Rentz et al., 1998, Schmitz et al., 1995]
6. Acidification aquatic and terrestrial [Heijungs et al., 1992; Schmitz et al., 1995]
7. Nutrification of water [Heijungs et al., 1992; Schmitz et al., 1995]
8. Photochemical oxidant formation [Heijungs et al., 1992; Schmitz et al., 1995]
9. Consumption of land [Heijungs et al., 1992; Schmitz et al., 1995]
10. Pollution (noise and odour) [Heijungs et al., 1992; Schmitz et al., 1995]
11. Health hazards at place of work (industrial safety) [Heijungs et al., 1992]
12. Waste heat and radiation [Heijungs et al., 1992; Schmitz et al., 1995]
13. Hazardous waste [Rentz et al., 1998]
14. Negative effects on environmental beauty and loss of biotopes ('nature conservation') [Heijungs et al., 1992]
15. Biodiversity [Heijungs et al., 1992]
16. Protection of the maritime environment [Rentz et al., 1998]

Although these impact categories are still not complete and disputable in several aspects, this approach has probably the best scientific research background for pointing out the relation between emissions and their potential ecological impacts. Therefore, at least hints for the most important environmental aspects of production and consequently for ecological improvement might be expected [Rentz et al., 1998]. The environmental impact categories obtained from the inventory analysis serve as the environmental requirements for the present study.

4. *Improvement Phase*

   In the traditional LCA method described by Consoli et al. [1993], improvement assessment has been defined as the last and final step in the LCA method. Improvement analysis provides starting points for the redesign of the product and processes concerned and the use of different materials [Schaltegger et al., 1996, p. 6; Heijungs et al., 1992, p. 93]. However, ISO 14040 refers to this last phase as "Interpretation" which points out that the development of conclusions do form an integral part of an LCA study [Frankl et al., 2000, p.23]. Although this phase is not yet a fully established phase in LCA study, this phase is the most productive for a company to consider since the global view of the product life cycle provides new insights and improvement opportunities. In the first case, improvement is normally related to product development, product planning or changes in the different processes and activities, or in the infrastructure of a product system. In the second case, improvements might be achieved through environmental regulations by authorities, by environmental labelling etc.

LCAs strengths derive from its roots in traditional engineering and process analysis. Often the purpose of an LCA study is to compare two or more alternatives of a product with respect to its environmental qualities. It is important to note that LCA is also a tool for sustainable product development (process design and product assessment) and not a legislative supervision tool [Potting, Moeller & Jensen, 1997; USEPA, 1993]. Manufacturers, consumer product companies and their suppliers can use LCA as a strategic tool to study the environmental impacts of their products and services at every stage of their life cycle, and to seek out opportunities for competitive advantage. It is among the most instructive management tools for getting insights into product related environmental impacts. However, critics have pointed out a number of serious limitations to the LCA methodology.

These include:

- Defining system boundaries for LCA is controversial;
- LCA is data-intensive and expensive to conduct;
- Inventory assessment alone is inadequate for meaningful comparison, yet impact assessment is fraught with scientific difficulties;
- LCA does not account for other non-environmental aspects such as product quality, and economic considerations that affect product competitiveness;
- LCA cannot capture the dynamics of changing markets and technologies;

Furthermore, in all types of applications for improvements, LCA data and information could be used as one part of the decision support documentation [Brunn, 1999, p.19; Brunn et al., 1996; Guinee, 1995, p.5], which is also the case in the present study. Improvement assessment can be considered as a bridge between the LCA method and different types of decision models, where the interpretations from the LCA studies are used as decision support by the decision makers. Hanssen et al. [1995] noted that different types of applications for improvements will have different requirements to the various stages in the LCA method. The different types of applications will thus influence on the LCA method, as it is applied in different decision models. On the other hand, the LCA approach will also influence the design of the decision model, the types of decisions taken, and the content of the decisions. In total, the combined LCA method and a decision model will be specific for each type of application, and both methods/models will be modifications of the standard methods. Some LCA softwares available in the market are listed in Appendix B.

4.7.1 Streamlined or Abridged LCA Philosophy

If no limitations to time, budget expense, data availability, resources, and analytical approach existed, a comprehensive LCA as described in the preceding section would provide an ideal advice for improving environmental performance. In practice, however, these limitations are always there like in the present research work too. The question of data availability, in particular, as it relates to product design and manufacture deserves attention. Experts agree that roughly 80 percent of the environmental costs of a product are determined at the design stage, and that modifications at later stages of product development will have only very modest effects [Graedel, 1998, p. 87]. The ideal time, then, to conduct LCA analysis is at early design phase. As a consequence, detailed LCAs cannot be regarded as providing rigorous quantitative results, but rather as providing framework upon which more efficient and useful methods of assessment can be developed. Techniques that purposely adopt some sort of simplified approach to life cycle assessment are called streamlined life-cycle assessments (SLCA). SLCA is an assessment that is complete and rigorous enough to be a definite guide to industry and an aid to the environment, yet not so detailed as to be difficult or impossible to perform.

Keith Weitz of North Carolina’s Research Triangle Institute and his co-workers [Graedel, 1998, p. 88] identified nine approaches to abridge LCA. These approaches are screening the product with an inviolates list; limiting or eliminating components or processes deemed to be of minor importance; limiting or eliminating life-cycle stages such as eliminating the upstream stages (resource extraction); inclusion of only selected environmental impacts or inventory parameters; limiting consideration to constituents above threshold weight or volume values; limiting or eliminating impact analysis; use qualitative rather than quantitative information; and finally eliminating interpretations or recommendations. Further discussion about these approaches can be consulted in Graedel [1998, p. 88]. In addition to this, there are several alternative approaches that have been put forward by individual corporations, consulting firms, and professional associations as suitable techniques for SLCA. Many of these approaches are gravitated toward a matrix. One dimension of this matrix is the life-cycle stages, and the other is a list of environmental impacts or other relevant parameters. Some of these SLCA approaches include Migros concept, UBC/IBM SLCA approach, Dow chemical company matrix, Monsanto matrix, Motorola’s SLCA approach, Battelle’s pollution prevention factors approach, and Jacobs engineering’s SCLA approach. Detailed explanation of these SLCA techniques can be referred in Graedel [1998]. Graedel, Allenby & Comrie [1995] and Graedel & Allenby [1996] developed one of these SCLA approaches. In their approach, a matrix (5 X 5) combined with target plots is constructed to estimate the potential for improvement in environmental performance of products and processes. This assessment system, in the case for environmentally responsible products (ERPs), has the following characteristics: it lends itself to direct comparisons among rated products or processes; it is usable and consistent across different assessment teams; it encompasses all stages of product or process life cycles and all relevant environmental stressors; and it is simple enough to permit relative quick and inexpensive assessments to be made. The assessors (engineers, designers, and/or managers) study the product or process design, manufacture, packaging, in-use environment, and likely disposal scenario and assign to each element of the matrix an integer rating from 0 (highest impact, a very negative evaluation) to 4 (lowest impact, an exemplary evaluation). These ratings are based from assessor's experience, a design and manufacturing survey, appropriate checklists, and other information. An example of this rating procedure can be consulted in the appendix of Graedel [1998, pp. 235-264]. After an evaluation has been made for each element, the overall environmentally responsible product rating (R_{ERP}) or environmentally responsible process rating (R_{ERPS}) is computed as the sum of the matrix element values as shown below:

$$R_{ERP} \;\; or \;\; R_{ERPS} = \sum_{i} \sum_{j} m_{i,j} \quad (4)$$

where:

i is the row of the matrix (life cycle stages)

j is the column of the matrix (environmental stressors)

m_{ij} is the element of row i and column j

Although the equations for the calculation of product and process ratings are similar, the product assessment matrix differs only from the process assessment matrix in terms of their life cycle stages [Graedel, 1998, p. 111]. For the product assessment, the life cycle stages are pre-manufacture, product manufacture, product delivery, product use, refurbishment, recycling and disposal. While for process assessment, the life cycle stages are resource provisioning, process implementation, primary process operation, complementary process operation, and refurbishment, recycling and disposal. Graedel [1998] suggested the use of Pareto target plots to display the assessment matrices more succinctly and provide a better view. The target plots for alternative designs of the same product permit quick comparisons of environmental attributes. To construct these target plots, the value of each element of the product or process assessment matrix is plotted at a specific angle. For instance, in a 25-element matrix, the angle spacing is 360/25= 14.4 degrees. The advantages of this approach are that the definition of functional units becomes less important, allocation problem is avoided and additionally it is less quantifiable and less thorough.

4.7.2 Pros and Cons of SLCA

SLCAs's superiority to comprehensive LCAs can be demonstrated in the following ways [Graedel, 1998, p.97]:

- SLCAs are much more efficient, typically taking several days of effort rather than several months

- SLCAs are much less costly. They are often capable of being done by existing staff and within existing job departments.

- Many SLCAs are usable in the early stages of design, when opportunities for change are great but quantitative information is sparse

- Finally, SLCAs are much more likely to be carried out routinely and can be applied to a wide variety of products and industrial activities.

However, SLCAs are inferior to LCA in the following aspects:

- SLCAs have little or no capability to track overall material flows. Within a corporation, for example, SLCAs on all products might well indicate whether a particular material was used but not whether its use in a particular product was a significant fraction of total corporate usage.

- SLCAs have minimal capability to compare completely dissimilar approaches to fulfilling a need.

- SLCAs have minimal capability to track improvements over time, e.g. to reliably determine if a product is environmentally superior to its predecessor.

Thus, SLCAs are more reasonable to conduct while recognising their limitations at the early design stage. The results of SLCAs are often regarded as “approximately correct”. In the present study, the idea behind SLCA is adopted in the development of methodology in chapter 7 to account less data requirements, few days of effort rather than several months, and particularly its usability in the early stages of design.

4.7.3 Imprecision and Uncertainty in LCA

One commonly ignored aspect in many life cycle assessment (LCA) studies is the issue of imprecision and uncertainty of data, e.g. emission data and system design variables. Schaltegger et al. [1996, p. 54] argued that LCA’s results without “confidence limits“ are questionable from a scientific point of view, and from the view of the users of the results, it is dangerous because they may lead to misjudgements. While conducting LCA, imprecision that will be encountered includes errors in quantities; stochastic (statistical) errors due to measurement; exact error intervals and vague error intervals; and other errors such as systematic errors (occur when the calibration model is not correct or when the structure of a system is not included completely in the calculation model) and intrinsically vague data (when data are sometimes used even when meaning cannot be simplified to one crisp number).

Additionally, there is a problem of data availability, which is critical in the case when new product concepts are evaluated with respect to their environmental performance at the early stage of product development. As a consequence, in most LCA studies, heterogeneous data coming from different sources are used. Specifically, in the idea phase of product development, uncertainties in information with regard to material composition, design, efficiency, life span, production technology and market volumes of a new product concept are encountered. Because of this limitation in data requirements at the early phase of product development, one determines the data needed through estimation, e.g. estimating emissions of alternative product improvement concepts based from the environmental performance of a reference system. However, the errors involved in performing such estimations by analogy could be very large.

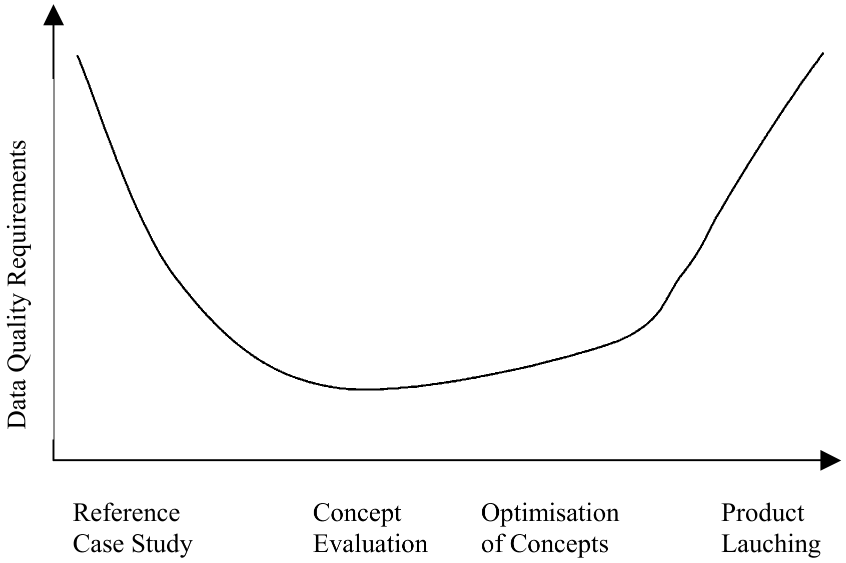
Nevertheless, this problem of imprecision and incompleteness of design data is not only limited in the case of LCA studies, but rather it is a general concern for the product development team of the company that makes decisions under uncertainty. Figure 4-4 shows the general trend on changes in data quality requirements throughout the different stages of product development. Similarly, this tendency could also reflect the data quality requirements for LCA when one is assessing the life cycle environmental impacts of a product. According to Figure 4-4 below, the data quality requirements for LCA changes in the following conditions [Hanssen et al., 1996]:

- In the initial stage in doing an LCA study of a reference product, high quality LCA data is required;
- In the concept definition and evaluation stage, the data quality requirements for the different alternative concepts are expected to be low because of the general high level of uncertainty;
- In the optimisation stage, the data quality requirements of LCA data generally increases as the selected product concept is optimised and manufactured;
- In product launching, accurate or high quality LCA data requirements of the chosen product concept are needed to be used for marketing the new product to the customers

The term “data quality”, as defined by Weidema [1993, p.58], encompasses a number of different components, including representativeness; reliability/verifiability; accessibility;

reproducibility; robustness; uncertainty/levels of confidence in data; completeness: dealing with missing or partial data; source/pedigree (including potential for bias, actual measurement versus engineering estimate, subsystem or process-specific versus aggregated, etc.); age, frequency and method of collection (including "maturity" issues: how sensitive are data to passage of time?); variability (need for additional data to characterise variability: ranges, high/low, variation in value under different operating conditions, etc.); statistical description (mean/median, confidence intervals, standard deviation, standard error, etc.), geographic scope of data (e.g. site-specific versus industry-averaged).

Thus, imprecision and incompleteness of data requirements in LCAs should be effectively addressed. Schaltegger et al. [1996, p. 51] & Weidema [1993, pp. 51-52] recommended that appropriate tools should be used to support LCA studies. These tools include statistics, calculation of maximum error and the use of fuzzy set theory. Statistics provide models of imprecision based on probabilities. Error limits method determined the absolute maximum errors in measurement. Fuzzy set theory enables one to set up possibility distributions for imprecise or vague data and therefore to handle those data even when no probabilities are known [Zadeh, 1965].



Source: Hanssen et al., 1996, p.14.36.

Figure 4-4 Changes in data quality requirements throughout the different stages of product development

4.7.4 Selected Related LCA Studies

In the succeeding paragraphs, selected studies are reviewed to know the extent of LCA's application to different areas.

Several possible uses of LCA have been discussed by Baumann et al. [1994a] and by several authors in Rydberg et al. [1994]. These applications are coupled to decision-making concerning products by different actors in society. In Table 4-3, a selection of potential applications of LCA is given. LCA can be used for quite different purposes such as for bottleneck identification and product innovation in industry, for marketing and information about consumers, for strategic planning within companies and for policymaking. A great number of applications for LCA have also been performed, which includes analysis of company's products, product development, for marketing and labelling use, process development and optimisation, choice of suppliers and raw materials, in training programmes and analysis of line of business. LCA has also been used in such wider management areas such as technology management and economic theories about innovation and entrepreneurship [Ulhoi, 1996].

Table 4-3 Selection of Potential Applications of LCA

Role	Actors	Application
Producer	Manufacturing companies	Redesign Process pollution prevention Raw material substitution Purchase requirements Extended producer responsbility
User	Authorities Manufacturing companies Private consumers NGOs	Product Choice User behaviour including internal recycling Disposal choice including external recycling
Policy Maker	Authorities Corporate Policy Makers	Product policy (e.g. bans, ecolabelling) Waste management policy
Interest Group	Environmentalists Trade Association Consumer organisations Labour unions	Consumer guiding Environmental labelling Information distribution

Source: Rydberg in Misra (ed.), 1996, p.401

Pedersen & Christiansen [1992] conducted a comprehensive literature review and found that a large proportion of LCA studies had been carried out for packaging products, primarily for comparison of different types of products. Allenby [1993] reported that many of the pioneering efforts to implement LCA and the more comprehensive DFE methodologies have been made by private firms. AT&T, for example, has developed an internal DFE module for its "Design for X" product design system. The X stands for any parameters that can be considered in the design process. Volvo, in conjunction with the Federation of Swedish Industries and the Swedish Environmental Research Institute, had developed an Environmental Priority Strategies (EPS) system, which attempts to summarise the environmental impact of materials expressed in environmental load units (ELUs). In Germany, Siemens developed an "Eco-balance" system that is designed to inform design engineers and managers about correct material and process choices within existent economic and competitive constraints.

Bloemhof-Ruwaard et al. [1995] explored the combination of life cycle analysis, multiple criteria decision-making and linear programming to assess environmental impacts of different vegetable oil products and processes. Vold & Roenning [1995] conducted a study on the life cycle assessment of 1000 kg of cement and 1 m^3 of concrete and reported that the emissions and consumption of fossil fuels were mainly generated in the clinker burning process. Hedelmalm and Segerberg [1995] compared various interconnection techniques or printed board assemblies with the use of LCA.

Fava [1995] stated that when one examines organisation's operations, it is the selling of products that drives the success of the business. An implication of this to life cycle thinking is the incorporation of environmental considerations into a product design and development process to manage the product's interface with the environment. The interface with the environment is from extraction of natural resources to obtain materials to manufacture product, to fuels such as coal and gas to produce energy and electricity and to the ultimate disposition of the final product. It would be interesting to consider if strategies are developed (e.g. pollution-prevention) to maximise the continued use of products and materials while minimising environmental releases and energy consumed over the entire life cycle. Fava further suggested that a tool (or a series of tools) that follows the design process, which embeds life-cycle information with business, financial, and technological measures and easy to use is needed. These tools will integrate the product life cycle and the environmental life cycle. He pointed out the use of QFD to define the technical parameters and consequently the operational characteristics. LCA's application when linked with business, technical, and cost analyses should be a part of an overall design for environment (DFE) initiative.

Moreover, using LCA, broad classes of product alternatives can be compared (e.g., cloth vs. diapers), products can be certified as environmentally friendly (e.g., retreaded tires in Germany), or alternative manufacturing processes can be compared for a particular product. Brunn et al. [1996] conducted a comparative LCA of the different utilisation processes used for sulfuric acid (H_2SO_4) with the aim of supporting a cost-benefit analysis and of identifying potentials within the chain of each utilisation process itself. The following three processes were examined: a) the production of gypsum in the work of Ciba-Geigy Corporation; (b) thermal reductive cracking with the production of liquid SO_2 in foodstuff quality; and c) thermal cracking and oxidation with the production of new H_2SO_4 96%. Golonka and Brennan [1996] applied the method of life cycle assessment to process selection for pollutant treatment in Australian metallurgical smelters. Kniel, Delmarco and Petrie [1996] used LCA to quantify and compare the environmental performance of a number of alternative process designs in nitric acid production. Costic et al. [1996] estimated the environmental performance of conventional lead-based solders and their substitutes using LCA. Donaldson et al. [1996] conducted a life cycle assessment of a telecommunications semiconductor laser. Pollock and Coulon [1996] made an extensive study of LCA for a Hewlett-Packard (HP) inkjet print cartridge involving over 100 HP people and many of HP's suppliers. Terho [1996] carried out LCA for telecommunication cables including improvement assessment. Van Mier, Sterke & Stevels [1996] performed a life cycle study on a 17" Philips-branded monitor and showed that there is a strong positive correspondence between economical and environmental aspects. Graedel et al. [1996] developed an environmentally responsible product assessment matrix, which uses checklist to simplify the process of performing LCA.

Chubbs and Steiner [1998] used life cycle assessment for evaluating the environmental impacts of steel. Anderson et al. [1998] examined the feasibility of combining the concept of sustainability principles and the life cycle assessment methodology. They used a qualitative-based tool to incorporate sustainability in product development and strategic planning. Kasai [1999] explored the use of life cycle assessment for evaluating the environmental burdens of automobiles quantitatively.

4.8 Brief Chapter Conclusion

Within this chapter, it has been found out that it is feasible to streamline or simplify a life cycle assessment to account for less data requirements, few days of effort rather than several months, and particularly its usability at the early stage of product development process. Some of these streamlined approaches include limiting or eliminating components or processes deemed to be of minor importance; inclusion of only selected environmental impacts or inventory parameters; limiting consideration to constituents above threshold weight or volume values; limiting or eliminating impact analysis; use qualitative rather than quantitative information; and finally eliminating interpretations or recommendations. Moreover, it is also discovered that in many LCA studies, imprecision and uncertainty are neglected despite the fact that these aspects are very important and should be taken into account in conducting the assessment, particularly if this evaluation will be done at the early stage of product development. Specifically, the environmental emissions and consumptions for the product system improvement alternatives are estimated with respect to the environmental performance of the reference product system. These relevant issues will be considered in the development of conceptual methodology in Chapter 7.

The next chapter discusses the importance of considering economic aspects at the initial stage of product development with the aid of life cycle cost analysis.

5 Economic Consideration and Life Cycle Costing Methodology

Other than meeting the important requirements of quality and environmental performance, cost or economic aspects that are usually included in any company's decision making activities should also be considered at the early stage of product development to judge whether it is economically feasible to improve or develop a product system. Peters and Timmerhaus [1991, p.5] argued that no design project should proceed to the final stages before costs are considered, and cost estimates should be made throughout the early stages of the design when complete specifications are not available. In this chapter, it will be pointed out that estimating the cost of a product system is much more complex than estimating the cost of a new piece of equipment because many variables and intangibles are involved. However, cost consideration is necessary in deciding whether the development of new product system is worth pursuing and further capital should be invested in the product improvement project.

5.1 Design for Economic Feasibility

Many authors have reported that a large portion of the total cost of a system[1] is committed on the basis of decisions made early in the system life cycle although only 5% to 10% of the overall cost is actually spent on this stage [Asiedu et al., 1998; Oakley, 1993; Graedel, 1998, p. 87; Dowlatshahi, 1992; National Research Council, 1991]. Similar finding has been claimed by Port [1990] in the automobile and electronics industry that up to 80% of product life cycle costs are committed during the concept and preliminary design stages, and that the cost of design changes increases steeply as a product proceeds into full-scale development and prototyping. Thus, in addressing the economic aspects of a system, one must look at total cost as sum of costs in all phases of the life cycle, and consider them particularly during the early planning and conceptual design stages when major decisions are made that significantly impact all subsequent activities. Life cycle cost, when included as a parameter in the systems engineering process, provides the opportunity to design for economic feasibility [Fabrycky & Blanchard, 1991, p. 2]. Fabrycky et al. further added that it is through a life-cycle approach to engineering that economic competitiveness can be enhanced.

5.2 Life-Cycle Costing

Throughout the product system life cycle, there are many decisions required, of both technical and a non-technical nature. The majority of these decisions, particularly those at the earlier stages, have life-cycle implications and definitely affect life-cycle cost. Life-cycle cost (LCC)

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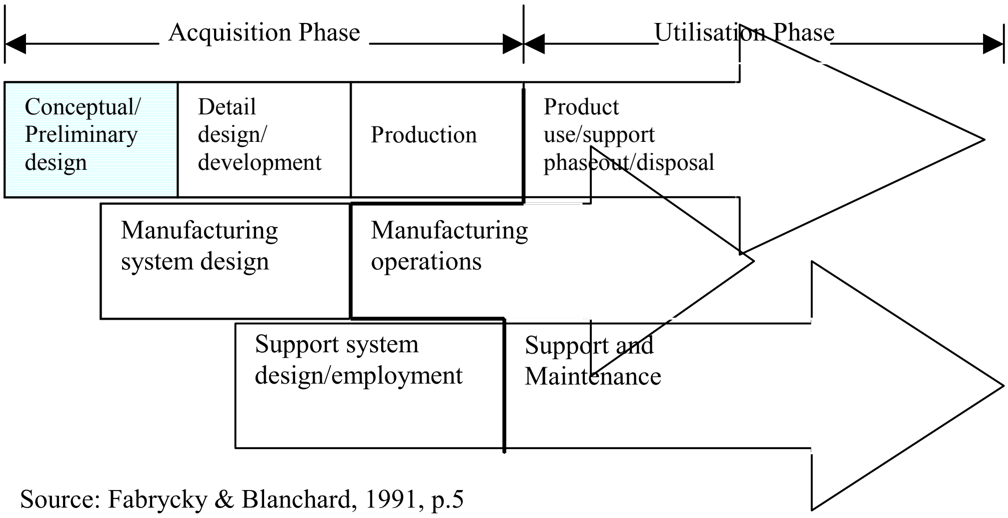
[1] For definition purposes, "a system may be considered as a nucleus of elements structured in such as manner as to accomplish a function designed to satisfy an identified need. A system may vary in form, fit, function and is discussed at various levels. A system can be considered to be a product, but not all products are systems, since the above characteristics may not prevail (e.g. radio without an operator) [Parnaby, 1995; Fitzgerald, Fitzgerald & Stallings, 1981, p. 5; Blanchard, 1976, p. 5].

refers to all costs associated with the system or products as applied to a defined life cycle. It is the total cost that a firm incurs, from the time of purchase until the disposal of any wastes or by-products and beyond, as long as liabilities or other costs may remain [Fiksel, 1996, p. 135]. It is determined by identifying the applicable functions in each phase of the life cycle, costing these functions, applying the appropriate costs by function on a year-to-year schedule, and ultimately accumulating the costs for the entire span of the life cycle. In contrast, Frankl et al. [1999, p. 21] defined life cycle costing differently and considered it as an inventory and analysis of economic implication of environmental impact of a given product during its life cycle.

The LCC method has been used within systems engineering in the industry for many years already. The life cycle and the major functions associated with each phase are illustrated in Figure 5-1. The program activities in Figure 5-1 have been classified into two basic phases: the acquisition phase and the utilisation phase. Activities progress from the identified need through conceptual/preliminary design, detail design and development, production and/or construction, and product utlisation.



Source: Fabrycky & Blanchard, 1991, p.5

Figure 5-1 The product, process and support life cycle

The life-cycle or concurrent design approach for bringing competitive products into being must go beyond consideration of the life cycle of product itself. It must simultaneously embrace the life cyle of the manufacturing process as well as the life cycle of the product support system. Thus, there are three coordinated life cycles progressing in parallel, as illustrated in Figure 5-1.

The need for the product comes into focus first. This recognition initiates conceptual design activity to meet the need. Then, during conceptual/preliminary design of the product, consideration should be given simultaneously to its ease of manufacture. This gives rise to a parallel life cycle for bringing a manufacturing capability into being, requiring many production-related activities to “make ready” for manufacturing. Also shown in Figure 5-1 is another life cycle of great importance which is often neglected until product and production design is completed. This is the life cycle for the logistic support activities needed to service the product during use and to support the manufacturing facility during its duty cycle. Logistics and maintenance requirements planning should begin during product conceptual/preliminary design in a coordinated manner. The objective behing engineering for the life cycle (in a concurrent manner) is to ensure that the entire life of a system is considered from inception. An engineering design should not oly transform a need into a definitive product configuration for customer use, but should ensure the design’s compatibility with related physical and functional requirements. Further, it should take into account life-cycle outcomes as measured by performance, effectiveness, producibility, reliability, maintainability, supportability, quality and cost.

In general, life cycle costs fall into categories based on organisational activity over the life cycle. According to Fabrycky et al. [1991 & 1981] and Blanchard [1978 & 1976], these general categories include the following:

- *Research and development cost.* This type of cost includes initial planning, market analysis, feasibility studies, product research, engineering design, design documentation, software, test and evaluation of engineering models and associated management functions.

- *Production and construction cost.* This category of cost comprises industrial engineering and operations analysis, manufacturing (fabrication, assembly, and test), facility construction, process development, production operations, quality control, and initial logistic support requirements (e.g., initial consumer support, the manufacture of spare parts, the production of test and support equipment, etc.)

- *Operation and support cost.* This type of cost includes consumer or user operations of the system/product in the field, production distribution (marketing and sales, and transportation), and sustaining logistic support throughout the system/product life cycle (e.g., customer service, maintenance activities, supply support, test and support equipment, transportation and handling, technical data, facilities, system modifications, etc.)

- *Retirement and disposal cost.* This category of cost comprises disposal of non-repairable items throughout the life cycle, system/product retirement, material recycling, and applicable logistic support requirements. This is the same with the cost that accounts the implementation of waste management for a particular product.

The application of life-cycle costing methods in system/product design and development is realised through the accomplishment of life cycle cost analyses (see section 5.4 for explanation). The “full life cycle” of a product or material begins as a decision is evaluated and a choice is made to acquire the product or material, or to acquire a component or system containing the substance. Costs are then incurred throughout the acquisition process, during handling or storage prior to use, throughout the use of the product or substance or equipment, and due to disposal of any wastes or residuals. In many cases costs will be incurred after disposal as well. Cost components may be incurred immediately, e.g. at the time of purchase or use, or they may be deferred, such as certain record-keeping costs or future legal liabilities. In general terms, one can define the life-cycle cost of a material or product as:

Life-cycle cost = **Cost of acquisition** (including direct purchase cost, handling or transportation costs, record keeping, etc.) + **Cost of use** (including the direct costs of use, associated labour and other material costs, training and management costs, occupational liabilities, costs of waste minimisation efforts, etc.) + **Cost of disposal** (including treatment costs, actual disposal costs, costs of record keeping and management, etc.)+ **Post disposal cost** (including long-term record keeping, potential liabilities, etc.) [Fiksel, 1996].

Table 5-1 shows examples of life cycle cost elements. However, it should be noted that all life-cycle costs might be difficult (if not impossible) to predict and measure.

Table 5-1 Examples of Life-Cycle Cost Elements

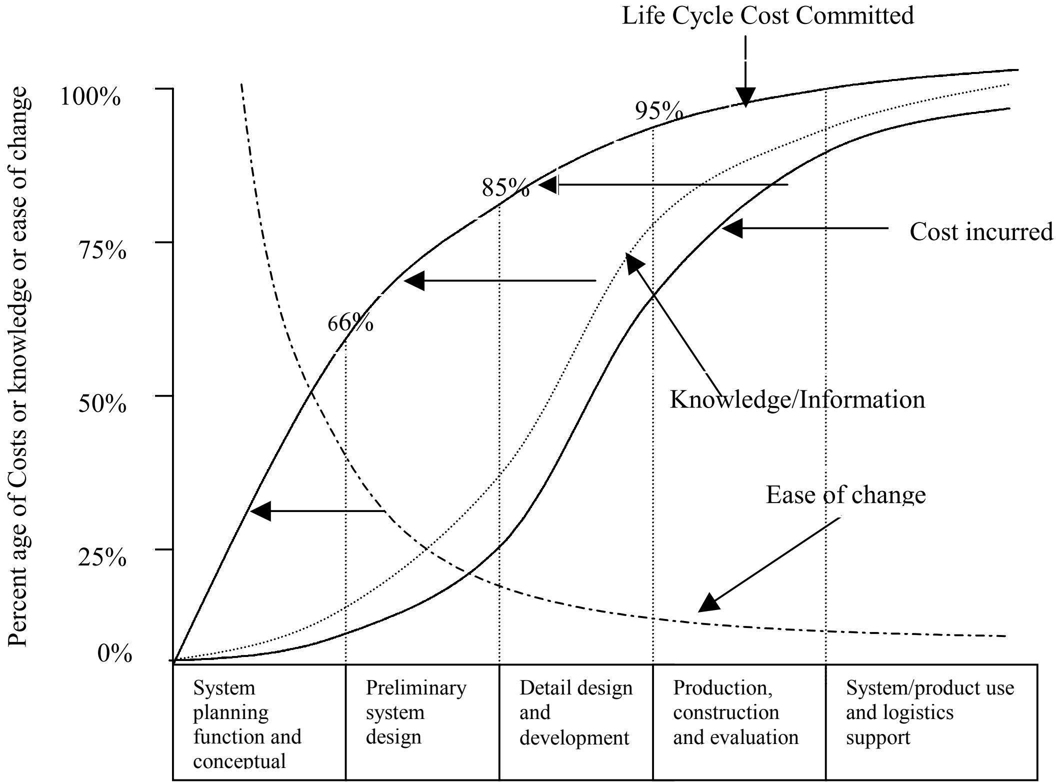
Type of Cost	**Stages in life cycle**			
	Acquisition	*Use*	*Disposal*	*Post disposal*
Direct	Purchase Taxes Shipping Financing	Labour Equipment Maintenance Inspection	Transport Storage Recycling Treatment Disposal	Insurance
Indirect	Handling Storage Record Keeping	Delivery to job site Training Industrial Hygiene Regulatory compliance	Training EH&S	Record keeping Monitoring
Uncertain	Spills and accidents while handling or in storage	Spills and accidents while in use Equipment failure Occupational liabilities	Accidents or spills Compliance with new regulations	Legal liabilities due to site contamination

Source: Fiksel, 1996, p. 138.

5.3 Cost Emphasis in the System Life Cycle

Since the major portion of the projected life cycle cost for a given system or product is made during the early planning and as part of system conceptual design, decisions that deal with system operational requirements, performance and effectiveness factors, maintenance concept, system configuration, quantity of items to be produced, consumer utilisation factors, logistic support policies and so on should be considered at this early stage. Such decisions made as a result of a market analysis or a design feasibility study actually guide subsequent design and production activities, product distribution functions, and the various aspects of sustaining system support. Thus, if ultimate life-cycle costs are to be optimised in designing for economic feasibility, it is essential that a high degree of cost emphasis should be applied in the early stages of system/product development.

Figure 5-2 reflects characteristic life cycle cost trend curves as related to actions occurring during the various phases of the life cycle. As illustrated in this figure, at least 66% of the projected life-cycle cost is committed by the end of the system planning and conceptual design stage, even though actual project expenditures are relatively minimal at this point in time. This curve varies with the individual system. However, it does convey a trend relative to the effects of decisions on ultimate life-cycle cost.



Source: Fabrycky et al., 1991, p. 13 ; Andreasen and Hein, 1987, p. 15; Moerup, 1993, p.5.

Figure 5-2 LCC committed, cost incurred, knowledge, and ease of change

5.4 Life-Cycle Cost Analysis

A life cycle cost (LCC) analysis may be defined as a systematic analytical process of evaluating various alternative courses of action with the objective of choosing the best way to employ scarce resources. The analysis constitutes a step-by-step approach employing life-cycle cost figures of merit as criteria to arrive at a cost-effective solution. The analysis is iterative in nature and can be applied to any phase of the system/product life cycle.

For each specific problem where there are possible alternative solutions and a decision is required in the selection of a preferred approach, there is an overall analysis process that one usually follows, either intuitively or on a formal basis. This process is comparable to the engineering analysis process. Formally, one should (1) define the need for analysis (involves clarification of analysis objectives, defining the issues of concern and bounding the problem), (2) establish the analysis approach, (3) select a model to facilitate the evaluation process after a cost breakdown structure has been established, (4) generate the appropriate data from existing data banks, advanced system/product planning data, individual cost estimates (through the use of different estimation methods), supplier documentation and engineering test and field data for each alternative being considered , (5) evaluate the alternatives, and (6) recommend a proposed solution in response to the problem at hand [Fabrycky et al., 1991, p. 500].

The basic steps in a typical life-cycle cost analysis are illustrated in Figure 5-3. These are briefly described below [Fabrycky et al., 1991, pp.326- 331].

5.4.1 Definition of Problem

An initial step involves the problem definition stage. Although this may appear to be intuitively obvious, it is not uncommon for one to delve into some in-depth analysis effort without first having defined the problem in detail. In essence, there mya be a requirement for a life-cycle cost analysis in evaluating alternative technologies as part of a feasibility study leading to a system design approach, alternative operational scenarious, alternative maintenance and support policies, alternative packaging schemes in equipment design, alternatives involving automation versus manual operations, alternative manufacturing approaches, alternative distribution and transportation methods, and so on. The analyst needs to define the problem, and describe the approach to be followed in resolviung the problem. There are life-cycle implications in almost all instances.

5.4.2 Identification of Feasible Alternatives

Critical in the accomplishment of any life-cycle cost analysis is the identification of feasible alternatives and the projection of each selected alternative in the context of the entire life

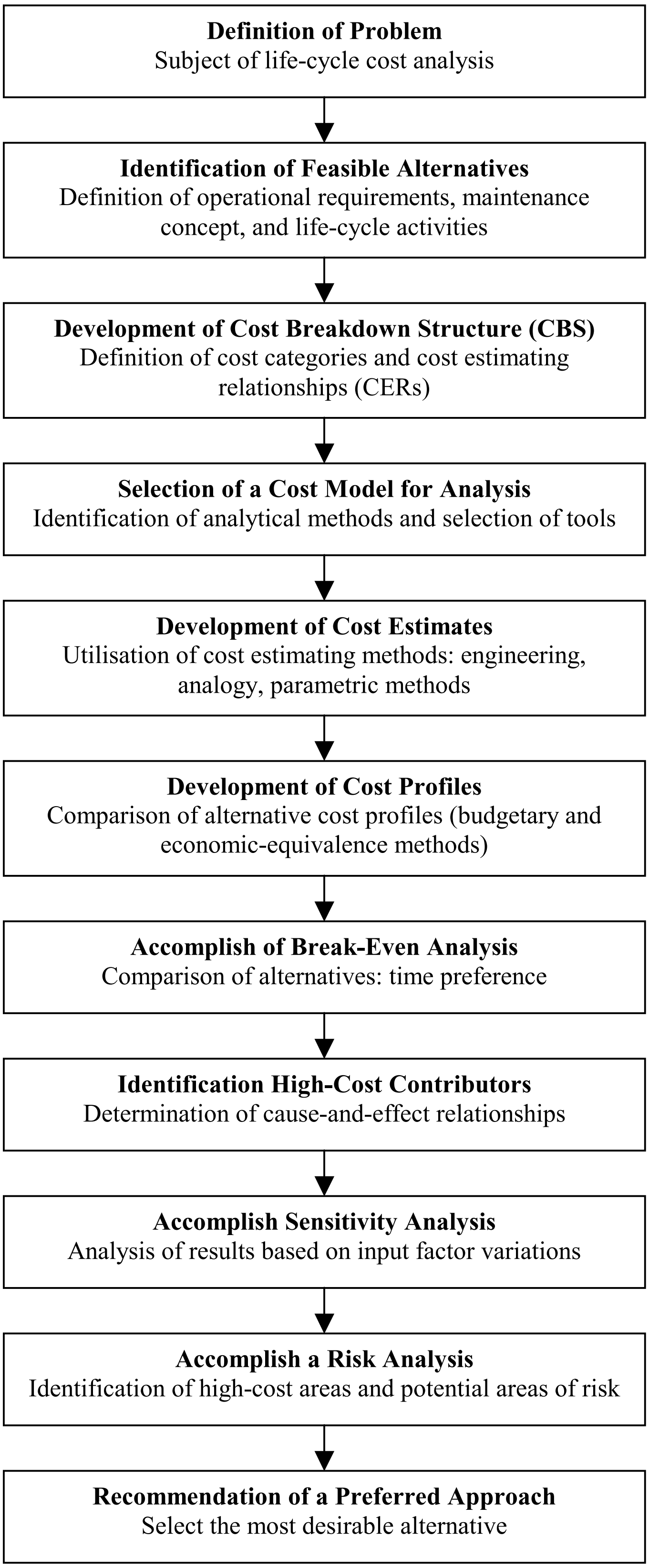


Figure 5-3 The Basic Steps in a Life-Cycle Cost Analysis

Source: Fabrycky et al., 1991, p.327

cycle. Associated with each alternative is a series of life-cycle activities in one form or another: that is, research tasks, design and development tasks, production and/or construction tasks, distribution and system operation, sustaining maintenance and support, retirement, equipment recycling and/or disposal. As the costs associated with each phase of activity affect other phases, it is necessary to view these activities in total. This, in turn, requires that the analyst define the system operational requirements and the maintenance concept as envisioned at that time. Although the details may change, a baseline must be established from the beginning.

5.4.3 Development of Cost Breakdown Structure (CBS)

Given the definition of alternative configurations (and associated activities) from a life-cycle perspective, the next step is to develop a "structure" for the allocation/collection of the costs as they related to the activities for each alternative being evaluated. The cost breakdown structure (CBS) must consider all future costs, must cover all life-cycle activities, must be developed to the depth required to provide the necessary visibility with regard to all elements of the system and/or program activities, and must allow for the presentation of costs on a functional basis. The CBS must be developed to provide the sensitivity required for the analysis effort.

5.4.4 Selection of a Cost Model for Analysis

Within the CBS, there are many different categories of cost, input-output parameter relationships, cost estimating relationships (CERs), and so on. With this in mind, the analyst needs to identify the appropriate analytical techniques/methods and a model that can be utilised to facilitate the analysis process. Care must be exercised to ensure that the tool selected is appropriate for the job at hand. There are many models in existence, advertised as being "the answer to all things" that are not sensitive to the problem being addressed.

5.4.5 Development of Cost Estimates

In response to the analysis requirements, the identified activities associated with the alternatives being evaluated, and the data structure within the CBS, the analyst proceeds with the cost estimating function. Cost estimates are developed using a combination straight engineering projection, estimating by analogy, using parametric methods, and so on. Cost estimating relationships (CERs), developed from data describing past experiences, are used to facilitate the estimating process. Cost projections are developed, including the effects of inflation, the utilisation of learning curves, and so on.

5.4.6 Development of Cost Profiles

When projecting costs out into the future for each alternative configuration being evaluated, cost profiles are developed. For the purposes of accomplishing a life-cycle cost analysis, a typical profile might be presented in three different ways to include (a) a discounted profile, using the time value of money concepts for the comparison of two or more alternatives on an equivalent basis; (b) a profile on a year-to-year basis in terms of today's dollars; and (c) a budgetary profile using inflationary factors, effects of learning curves, and so on, to allow for the evaluation of a single profile in terms of possible resource or budgetary constraints. While an economic analysis effort requires the time value of money considerations, a manager will often want to look at a profile presented in budgetary terms prior to making a decision in selecting a specific alternative.

5.4.7 Accomplishment of Break-even Analysis

When comparing the alternative cost profiles on the basis of the individual cost summaries, delta costs, and so on, it may at first appear that one alternative is clearly favoured over another. However, prior to arriving at a final decision, the analyst must determine the point in time when the preferred approach assumes the "position of preference". If *A* is preferred over *B* but *A* does not assume the preferred position until 11 years in the future, should *A* be selected as the preferred alternative? The analyst needs to develop a break-even analysis in order to determine the points in time when the different alternatives look good. The ultimate decision will not only be based on the cost profiles and the associated delta costs, but on the times in the life cycle when one looks better than the other. Of course, the analyst needs to consider such things as obsolescence, outside competition, and so on.

5.4.8 Identify High Cost Contributors

Given the results of life cycle analysis, the analyst may wish to identify those areas of potential risk and where possible improvements can be introduced with the objective of reducing the overall life-cycle cost.

5.4.9 Accomplish Sensitivity Analysis

When reviewing the output results of a life-cycle cost analysis, while identifying the high-cost contributors and the major „causes", the analyst should proceed further by identifying the specific input data elements that are used in the analysis process. These data elements, particularly those that can significantly affect the analysis results, should be investigated in terms of source, validity and reliability of the data, and so on. There may be certain input data elements, which have a large affect on the analysis results, that are highly "suspect" in terms of origin!

5.4.10 Accomplish a Risk Analysis

Potential areas of risk are reflected by those high-cost categories which, in turn, can be traced back to certain critical input factors. In the process of accomplishing life-cycle costing, including both the assessment and the feedback provisions for corrective action, it is the objective to identify and eliminate potential areas of risk early. However, if this process is not effective, the "outstanding" high-cost areas can be identified, noted in terms of probability of occurrence, and adequately addressed through an appropriate risk management program.

A life-cycle cost analysis may be accomplished in addressing a wide variety of problems at different stages of the system/product life cycle. Life-cycle cost analysis may be employed in the evaluation of alternative system/product operational, utilisation and environmental profiles, alternative product disposal and recycling methods, alternative management policies and their impact on the system, alternative system maintenance concepts, alternative procurement source selection for a given item, and many others. It is applicable in the initial structuring of system requirements, in the evaluation of design alternatives, and in the development of manufacturing/production approaches. It can be effectively utilised in assessing an existing system capability already in being by identifying high-cost contributors and costly problem areas. Life-cycle costing can be accomplished during conceptual design when limited input data are available and, of course, it can be accomplished later during detailed design and development when the system configuration is fairly well defined. Details and several examples in doing life cycle cost analysis can be found in Fabrycky et al. [1991].

5.5 Estimating Cost and Economic Elements

When cost factors are not easy to determine at the early stage of product development and economic information is not readily available, then costs eventually could be estimated [Allen, 1975; Popper, 1970, p.243]. Cost estimation is an endeavour that will result only in an approximation of what will occur. A cost estimate is an opinion based on analysis and judgement of the cost of a product, system, or structure [Peters and Timmerhaus,1991, p.150]. This estimation may be arrived at in either formal or informal manner by several methods, all of which assume that experience is a good basis for predicting the future. Estimating life-cycle costs requires the integration of information from many sources. The techniques used for cost estimation range from intuition at one extreme to detailed mathematical analysis at the other. Some of these methods include estimating by engineering procedures, estimating by analogy and parametric estimating methods [Fabrycky et al., 1991, pp. 145-147]. Nevertheless, since cost estimation involves subjectivity, the results of estimation may be imprecise or random. The largest sources of error in cost estimation are overlooking elements of cost [Peters and Timmerhaus, 1991, p.195]. Although there are only 3 estimating methods discussed here, there are several other estimating methods found in the literature [Popper, 1970; Greer and Nussbaum, 1990; Rentz, 2001]. The reason for considering only these three is that they are usually used for estimating product’s life cycle costs at an early stage of product development.

5.5.1 Estimating by Engineering Procedures

Estimating by engineering procedures involves an examination of separate segments at a detailed level [Ostwald, 1984]. The engineering estimator begins with a complete design and specifies each production task, equipment and tool needed, and material equipment. Costs are assigned to each element at the lowest possible level of detail. These are then combined into a total for the product and the system.

Time standards for production operations exist for many common tasks [Salvendy, 1992; Maynard, 1971]. These are usually developed by industrial engineers and constitute the minimum time required to complete a given task with normal worker skills and tools. Standards are best applied in engineering estimating procedures when a long, stable production run of identical items is contemplated. They are normally not useful in estimating for complex systems in which one of a kind to be fabricated.

Engineering estimating procedures may require more hours of effort and data than are likely to be available in the development of some systems or products. Combining thousands of detailed estimates into an overall estimate can lead to an erroneous result for the whole, which often turns out to be greater than the sum of its parts [Stewart, 1982]. The engineering estimator works from sketches, engineering drawings, or descriptions for some items that have not been completely designed [Lang, 1948]. One can assign costs only to activities that one knows about. The effect of low estimates may be compounded because detail estimating is attempted on only a portion of the labour hours. A number of production labour elements, such as planning, rework, coordination, and testing, are usually factored in as a percentage of the detail estimates. Other cost elements, such as maintenance, inspection, and production control, are factored in as a percentage of the production labour required. Thus, small errors in detailed estimates can result in large errors in the total cost estimate.

Another source of error in estimates made by the engineering method is the significant variability that occurs in the fabrication of successive units. Production runs of like models may be of limited length and often are subject to design changes.

5.5.2 Estimating by Analogy

When a firm is entering into a new activity such as product development, estimating by analogy can be very effective. Estimating by analogy can be done both at macro and micro levels. Most companies have extensive records of their operations, so that quick estimates of total product costs can be obtained from existing records [Peters and Timmerhaus, 1991, p. 195]. For example, at micro level, the direct labour hours required to make a component part may be estimated by referring to the hours required on similar jobs. The basis for the estimate is the similarity that exists between the known item and the proposed part. The cost of direct labour is sometimes estimated in relation to the cost of material. These relationships are known with reasonable accuracy for different kinds of activities. For example, the cost of labour to lay 1,000 bricks is approximately equal to the cost of bricks and the necessary mortar.

At all levels of aggregation, a great deal of estimation is performed by analogy. For example, project *A* required 10,000 direct labour hours and 4,000 equipment hours. Given the similarities and differences between project *A* and proposed project *B*, the direct labour hours and equipment hours might be estimated to be 8,000 and 3,200 respectively. By applying current labour-and equipment-hour rates, and an applicable overhead rate, a total project cost can be estimated. Or the estimator may find elements in project *A* that are analogous to elements in project *B*. From this, cost of project *B* may be estimated. In this example, analogy becomes part of the engineering method of estimating.

A major disadvantage of estimating by analogy is the high degree of judgement required [Fabrycky and Blanchard, 1991, p.146]. Considerable experience and expertise are required to identify and deal with appropriate analogies and to make adjustments for perceived differences. However, because the cost of estimating by analogy is low, it can be used as a check on other methods. Often it is the only method that can be used because the product or system is only in a preliminary stage [Allen, 1975].

5.5.3 Parametric Estimating Methods

The parametric method of cost estimating may utilise statistical techniques ranging from simple graphical curve fitting to multiple correlation analysis [Perry and Green, 1997, p. 9-63; Green and Nussbaum, 1990, p.245]. In either case, the objective is to find a functional relationship between changes in cost and the factor or factors upon which the cost depends, such as output rate, weight, lot size, and so forth. Parametric estimating techniques are perfect for cost estimating during a project's conceptual phase, and the tools connect technical and cost parameters together in a very effective way [US Government/Industry Joint Committee, 1995, p. 160].

Although parametric cost estimating techniques are preferred in most situations, there are cases in which engineering methods or estimating by analogy are required because the data for a systematic historical base do not exist. The product may utilise some new unfamiliar manufacturing method, thus invalidating data from previous items as a statistical base. There will always be situations in which analogy or engineering methods are required, but the statistical approach is judged to be sufficient in long range planning. Total cost may be estimated directly as a function of power output, weight, square feet, volume, and the like.

Industry-wide data or maintenance experience and energy consumed can be treated statistically and added to statistically estimated costs associated with the item itself.

Parametric estimating techniques will vary according to the purpose of the study and the information available. In conceptual design, it is desirable to have a procedure that gives the total expected cost of the product or system. Allowances for contingencies are to compensate for unforeseen changes that will have to be made. Later, as the product or system moves closer to detail design, it is desirable to have a procedure that will yield estimates of its component parts. Additional engineering effort can then be applied to reduce the cost of those components, which are found to be high contributors to overall cost.

Parametric cost estimating relationships are basically "rules of thumb" that relate various categories of cost-to-cost generating or explanatory variables of one form or another [Fabrycky and Blanchard, 1991, p.159]. These explanatory variables represent characteristics of system performance, physical features, effectiveness factors, or even other cost elements. Cost estimating relationships may take different forms (i.e., continuous or discontinuous, mathematical or nonmathematical, linear or non-linear and statistical distribution functions).

5.6 Life-Cycle Cost Management

Life cycle cost management (LCCM) is an application of integrated life cycle management concept, which is a comprehensive and flexible life-cycle framework for making plan, design, and operating decisions, explicitly considering costs and other fundamental business metrics together with environmental, quality, safety and other technical factors [Fiksel, 1996, p. 130]. The primary goal of life cycle cost management is to save money by making purchase, operating, and maintenance decisions based on the full life-cycle cost of a material, product, process, or service, which explicitly includes the costs of environmental, health, and safety issues. The scope of decisions and alternatives that can be addressed includes product and material selection and use, process design, waste management, and others. Secondary goals often include achieving pollution prevention, source reduction and waste minimisation targets. In many cases, the alternative with the lowest life-cycle cost also provides an opportunity for pollution prevention. However in other cases, a firm is required to make trade-offs between cost and other goals such as product quality.

5.7 Related LCC Studies

Fabrycky et al. [1991] presented in their book many case studies and examples about life cycle costing methodology. For instance, they showed how to perform comprehensive life cycle cost analysis for the alternatives of communication system procurement. Van Mier et al. [1996] applied life cycle costing in addition to eco-indicator for obtaining the life cycle cost and environmental profiles of a computer monitor. They found that economical and environmental aspects have strong positive correlation and that environmental improvement could lead to cost savings. Asiedu et al. [1998] reviewed several studies related to product life cycle cost analysis. They look at the issues of LCC analysis and the development of methodologies such as design for environment, design for quality and design for manufacturing to provide engineers with cost information during design. Beaver [2000] developed a total cost assessment (TCA) methodology in relation to life cycle analysis (LCA). In his research, he reported that the decisions that benefit from total cost assessment include process development, waste management decisions, pollution prevention alternatives, outbound logistics and many others. In a related research with regard to LCA and economic feasibility, a methodology for the economic assessment of best available techniques in the framework of the IPPC-Directive on a plant level has been proposed by Schultmann, Jochum and Rentz [2001] . This methodology accounts all costs that accrue by measures to prevent, to reduce, to utilise or to remove emissions into water, air and soil caused by industrial production processes.

5.8 Brief Chapter Conclusion

In the present study, the LCC analysis will be modified and simplified to adapt with regard to data availability and is used to compare product system improvement alternatives with respect to their costs in a life cycle perspective and consequently to find the best ranking improvement option.

Since, in many cases, the cost factors of the different alternative system improvement concepts will be difficult to obtain and not known with accuracy at the initial design stage of product development, they will be estimated here by analogy with reference to a baseline product system to calculate approximately their estimated life cycle costs. However, it should be pointed out that this cost estimation procedure is still very subjective and essentially depends on the accuracy of the experts' judgement and on complete familiarity with the products and processes considered.

In the next chapter, the concepts of fuzzy sets, the difference between fuzziness and probability, linguistic terms and hedges, multicriteria methodologies and other related information with relevance to uncertainty involved in decision making will be discussed in detail.

6 Fuzziness and Decision Making

In the last three chapters, selected theoretical concepts and methodologies related to economic, quality and environmental considerations for the initial conceptual stage of product development were reviewed. Nevertheless, it is found out that there is a limitation common among LCA, QFD and LCC methods if they are used at the early product design decision-making. This drawback is about the imprecision and incompleteness of design data available particularly at the early stage of product planning. Several researchers have reported that during the screening decision of concepts at the early stage of product development process, one is always confronted with a high degree of uncertainty because detailed information is not normally available and accuracy of estimating costs and emissions of the proposed concepts is not always feasible, other than the fact that subjectivity in rating the criteria still remains [Wang, 1999; Urban et al., 1993; Cooper, 1981]. For instance, when one evaluates the capability of different proposed product concepts to satisfy the environmental requirements established by LCA method (where initial data quality requirements are high), one usually bases his evaluation from environmental information (such as amount of emissions and consumptions) obtained from inventory analysis. However, one is confronted with inadequacy of quantitative data and also, in the case of proposed concepts which are still not yet implemented, one cannot determine the environmental performance of each of the alternatives with precision. Instead, one determines approximately the individual emissions and consumptions by analogy to a reference product system. Consequently, this imprecision and inadequacy of data affects the result of the environmental decision or selection of alternatives to be made. Another case is when evaluating the effectiveness of the proposed alternatives to meet the quality requirements in the case of using QFD methodology. Similar problems on inexactness and incompleteness of design information at the early stage result to difficulty in rating the relative importance of customer attributes, and assessing the relationships between customer attributes and design requirements. Also, it is assumed here that the capability of the proposed system improvement alternatives to satisfy the customer requirements is the same to that of a reference product system. Lastly, in the case of LCC, where one assesses the proposed product improvement concepts with respect to cost consideration, the costs involved in the product life cycle can not all be obtained and as a result, these costs are usually either assumed or estimated by analogy which also entails uncertainty.

Due to the problem on lack of adequate and of precise information at the early stage of a product development process, an assessment methodology that accounts this limitation should be used. In the present study, the use of “fuzzy linguistic term” is explored and found to be appropriate because it incorporates the uncertainty of data requirements and allows one to start with little information.

In the succeeding sections, some basic concepts of fuzzy set theory and multi-criteria methodology are discussed, and previous related fuzzy based decision making studies are reviewed. Given the massive amount of literature on this field, only the concepts relevant to the understanding of the present study will be presented.

6.1 Decisions and Fuzzy Logic

Decisions are usually made based on uncertain information. Decision-making involves subjectivity, which is a critical factor. For instance, expert opinions, which are subjective, are frequently used to assign importance weights to engineering characteristics in practice. In some cases, unconfirmed data and information need to be used to produce and process customer wishes and consequently result to a decision [Eversheim, Roggatz and Zimmerman, 1997; French, 1993]. Frankl et al. [1999, p.10] also reported that individuals and organisations have limited information processing capabilities because of incomplete information about possible courses of action, their ability to only explore a limited number of alternatives relating to a given decision and their incapacity to attach accurate values to outcomes. People are more prone to interference from biasing tendencies if they are forced to provide numerical estimates since the elicitation of numerical estimates forces an individual to operate in a mode which requires more mental effort than that required for less precise verbal statements. Moreover, Wilhelm & Parsaei [1991] and Zimmer [1983] asserted that humans are unsuccessful in making quantitative predictions, whereas they are comparatively efficient in qualitative forecasting. Nath and Lee [1983] argued that in essence, the human thinking is fuzzy in nature, and the human communication is in natural language, which is approximate, summarised and so fuzzy.

Fuzzy linguistic approach uses linguistic descriptions to define input relationships and the expected outcomes. The term “fuzzy” refers to its ability to deal with imprecise or vague inputs. Many authors have found that a fuzzy logic based approach is more appropriate to evaluate engineering requirements because it captures the uncertainties involved and has been very effective in solving multi-criteria decision making problems where data is ambiguous or defined in linguistic form [Klir and Bo, 1995; Terano, Asai and Sugeno, 1987]. Hisdal [1988] proposed that fuzzy logic could better handle inexact information and linguistic variables in a mathematically well-defined way, which simulates the processing of information in natural-language communication. For example, expressions such as: “high quality”, “low environmental impact”, or “low life-cycle cost” are imprecise. Within these phrases, the terms such as low, high, very low, medium and so on in a natural or synthetic language are values of linguistic variables. Linguistic variables are fully discussed in section 6.3. Thus, a systematic use of words to characterise values of variables, values of probabilities, relations between variables, and so on, constitute a linguistic approach usually described as fuzzy logic [Klir et al., 1995]. Nowadays, the principal applications of fuzzy logic are in consumer products, industrial-commercial systems, and decision support systems. Anderson [1994] reported that some of the benefits of applying fuzzy logic are (1) it eliminates the difficulties of mathematical modelling, (2) it allows the application/design engineer to describe inputs, rules and outputs in everyday language, and (3) it allows one to get started with very little information.

6.2 Difference Between Possibility (Fuzziness) and Probability

Possibility or fuzziness deals with the possible while probability deals with the probable [Lee and Zhu, 1995]. It is a type of imprecision that stems from a grouping of elements into classes that do not have sharply defined boundaries. Possibility is associated with the degree of feasibility or the sense of attainment, whereas, probability relates to the degree of likelihood, frequency, or proportion. This implies that what is possible may not be probable, and what is improbable may not be impossible.

There are many types of uncertainties. Probability models randomness while possibility models fuzziness where the events have no clear boundary. The concept of possibility, unlike probability, does not involve the notion of repeated experimentation. Thus, possibility can be used to model the imprecision of uncertainties, which are not susceptible to probability analysis or characterisation.

Another way to compare these two different approaches of modelling uncertainties is to consider the rules, which govern their aggregation. Possibility theory is usually based on the max-min aggregation while probability theory requires that the summation of the probabilities of all the possible outcomes must be equal to one. In possibility, intersection is modelled by the min-operator and union is modelled by the max-operator. This max-min operator for aggregating fuzzy relations is briefly illustrated in Appendix *A*. In probability, intersection of two independent events corresponds to the product operator and the union of two independent, mutually exclusive events corresponds to the sum operator. Thus, in a sense, the requirements of possibility are not as strict as that of probability.

Many of the particular characteristics of possibility theory are intimately connected with linguistics. For example, human language is frequently vague and approximate, which is exactly the same for fuzzy or possibility. Language is intimately connected with human activities and thus it is subjective and cannot be objective. Fuzzy set is also subjective, not like the objective requirements when probability is used.

In the next subsequent section, the concepts and mathematical representation of fuzziness or possibility is explained in detail.

6.3 Fuzzy Sets

Fuzzy set theory was formulated, around 36 years ago by Zadeh [1965]. This theory has one of its aims the development of a methodology for the formulation and solution of problems that are too complex or too ill-defined to be susceptible of analysis by conventional techniques. A fuzzy set presents a boundary with a gradual contour, by contrast with classical sets that present a discrete border. Intuitively, a fuzzy set is a class that admits the possibility of partial membership in it. Let *U* be the entire set (or called a *universe of discourse*) and *u* a generic element of *U*, then *U={u}*. A fuzzy subset $\tilde{A}$, defined in *U*, is

$$\tilde{A}=\left\{\left(u,\mu_{\tilde{A}}(u)\right)\,|u\in U\right\} \quad (5)$$

where $\mu_{\tilde{A}}(u)$ is designated as membership function or membership grade (also referred as degree of compatibility or degree of truth) of *u in* $\tilde{A}$. It deals with a subset $\tilde{A}$ of U, where the transition between full membership and no membership is gradual rather than abrupt. The membership function associates with each element *u*, of *U*, a real number $\mu_{\tilde{A}}(u)$, in the closed interval between 0 (nonmembership) and 1 (full membership). The grades of membership also reflect an "ordering" of the objects in the universe; it is interesting to note that the grade of membership value $\mu_{\tilde{A}}(u)$ of an object *u* in $\tilde{A}$ can be interpreted as the degree of compatibility of the predicate associated with $\tilde{A}$ and the object *u* (Munda, 1986, p.3]. The assignment of the membership function of a fuzzy set is subjective in nature, and in general, reflects the context in which the problem is viewed [Munda, p.4]. Membership functions may be built in two different ways [Munda, 1995, p.96]:

1. Deductively, with the use of formal models constructed according to specific hypotheses;
2. Empirically, with the use of two different methods:
    a. interpolating a finite number of degrees of membership,
    b. constructing a real model of a membership function and seeking to verify its empirical validity.

In the case for evaluation and decision models, the empirical approach is more suitable mainly because it greatly reduces the subjective component.

For example, let's consider the class of all real numbers that are much greater than 1. One can define this set as

$$\tilde{A}=\left\{u\,/\,u\ is\ a\ real\ \mathrm{n}umber\ and\ x\gg 1\right\}.$$

This set may be defined subjectively by a membership function such as

$\mu_{\tilde{A}}(u) = 0 \qquad for\ x \leq 1$

$\mu_{\tilde{A}}(u) = \dfrac{u-1}{u} \qquad for\ x > 1$

6.4 Fuzzy Relations

An important concept for fuzzy decision support systems is the concept of relation between elements of the sets. A fuzzy relation represents the degree of association between the elements of two or more sets and can be represented by membership grades. The concept of fuzzy relation is easily generalised to n-dimensions. A fuzzy relation between an element $x \in X$ and an element $y \in Y$, is defined in the X **X** Y space, designated by Cartesian product, which is the set of all dual pairs *(x, y)*. Thus a fuzzy relation $\tilde{N}$, defined in X **X** Y is the subset of the X **X** Y comprehending all dual pairs, where the association is represented as

$$\tilde{N}(x,y) = \{((x,y), \mu_{\tilde{N}}(x,y)) \mid (x,y) \in X \times Y\} \quad (6)$$

Considering two binary fuzzy relations $\tilde{P}(X,Y)$ and $\tilde{Q}(Y,Z)$, having the Y as in common, it is possible to perform the composition of these two relations. The result is a new fuzzy relation $\tilde{R}(X,Z)$, if and only if at least one element $y \in Y$ pertains simultaneously to

$$\tilde{R}(X,Z) = \tilde{P}(X,Y) \circ \tilde{Q}(Y,Z) \quad (7)$$

relations $\tilde{P}$ and $\tilde{Q}$. This composition can be denoted by

where $\circ$ is defined as symbol for max-min operator. Max-min is one of the aggregation operations, which is frequently used for binary fuzzy relations. It is the most popular and commonly used connective for fuzzy relations although there are still other non-common composition methods in the literature such as triangular norms, max-product and etc. [Bourke & Fisher, 1998; Adamopoulos and Pappis, 1993; Chen, 1985]. More discussion of fuzzy relations is largely documented in the literature (Zimmermann, 1996 and 1993; Klir & Folger, 1988; Zadeh, 1965].

6.5 Linguistic Variables and Representation

In this section, the concept of linguistic patterns is introduced and how linguistic variables can be mathematically represented.

A linguistic pattern consists of linguistic variables. A variable is normally thought of as a notion that can be specified by assigning to it certain numerical values. If one defines the variable A to mean “age” and specify $0 \leq A \leq 100$, one knows that the variable A can have all numbers between 0 and 100 assigned to it. A linguistic variable is a variable that admits as value words or sentences of a natural language, which can be represented as fuzzy sets. To understand easily the notion of a linguistic variable, regard it either as a variable whose numerical values are fuzzy numbers or as a variable where the range of which is not defined by numerical values but by linguistic terms. Zadeh [1973 & 1975] called this linguistic variable as a “variable of higher order”. Many studies showed that the concept of linguistic variables is very useful in dealing with situations that are too complex or too ill defined to be reasonably described in conventional quantitative expressions [Badiru & Arif, 1996; Zadeh, 1976 & 1975] such as when different conflicting evaluation criteria are taken into consideration.

A linguistic variable is characterised by a quintuple (*H, T (H), U, G, M*) in which *H* is the name of the variable; *T (H)* denotes the term-set of *H*, that is, the set of names of linguistic variables of *H*, with each value being a fuzzy variable denoted generically by *X* and ranging over a universe of discourse *U* which is associated with the base variable *u*; *G* is a syntactic rule (see section 6.5.1 for detailed explanation) for generating the names, *X*, of values of *H*; and *M* is a semantic rule (see section 6.5.2 for explanation) for associating with each meaning, *M (X)* which is a fuzzy subset of *U*. A particular *X*, that is, a name generated by *G*, is called a term. A term consists of a word or words which function as a unit and is called an atomic term. A term, which contains one or more atomic terms, is a composite term [Zadeh, 1972 & 1975; Zimmermann, 1986; Leung, 1988; Lee and Hsih, 2001].

For example, consider the linguistic variable named *H*= Temperature. Here the name of the linguistic variable is Temperature. Let’s say, the term-set, *T (Temperature) = {High, Very High, Not Very High, Not Very Low, Normal, Above Normal…}*. Each of the term-set denotes some value (in a fuzzy sense) to the linguistic variable, *Temperature*, and each of them is a fuzzy variable over the universe of discourse, say, 0°C to 100°C. The base variable here is *t°C*. All the components of the term-set can be generated by a syntactic rule, *G*. The meaning of High, i.e. *M (High)*, is a fuzzy subset over the universe of discourse 0°C to 100°C and its membership function may be given in terms of the base variable *t* as

$$\mu_{M(High)}(t) = f(t) \quad (8)$$

where *f (t)* is a suitable function of *t*. Thus, “Temperature is High” is a fuzzy linguistic variable whose value is high. The meaning of “High” is also a fuzzy subset whose membership function is given in equation (8). In this example, *High, Low*, and *Normal* are atomic terms, and *Very High, Very Low, Above Normal*, etc. are composite linguistic terms because two atomic terms were combined.

It is apparent from the above definition that a linguistic variable may be words or a sentence in a natural or artificial language, and its value is a not a number but is a word (words) which is a fuzzy variable whose meaning is a fuzzy subset in a universe of discourse. In general, the linguistic values of a variable are composites of atomic terms, which are linked together in the form, $X=X_1X_2X_3 \ldots X_n$, where X is the composite linguistic term, and X_i, $i=1,\ldots, n$, are atomic terms. For example, if X_1= *very*, X_2= *tall* and X_3= *man*, then $X_1X_2X_3 = X$ is the composite linguistic term, *very tall man*.

6.5.1 The Syntactic Rule

According to Zadeh's linguistic approach, there is no limit on the number of terms or linguistic values in a term-set [Zadeh, 1975 & 1976]. However, there exists a definite structure for the term-set of any linguistic variable. A term-set consists of primary terms, which are usually finite in number, and composite terms, which are various combinations or modifications of the primary terms. For example, for the linguistic variable "Temperature", the primary terms are high, low and normal. An infinite number of composite terms can be obtained such as very high, not very high, very low, not very low, above normal, below normal, etc.

Most linguistic variables have the same basic structure of term-set. For example, one can replace high by superior, normal by average and low by poor, one obtains the primary terms for the linguistic variable *Capability*. The same applies to many other linguistic variables such as the goodness of a management (good, average and bad), the rate of increase of a company's high profit (high, medium and low), quality (good, average and bad), importance (critical, important, unimportant), etc.

Generally, linguistic values or terms can be divided into four categories:

(i) Primary or atomic terms, e.g. *High, Low, Medium, Superior, Average, Poor* etc.

(ii) The negation 'not', and connectives 'and', 'or', e.g. *not High, not Low, not Poor, not Superior*, etc.

(iii) With linguistic hedges, e.g. *Very High, More or less Superior, Indeed Superior, Above Average, Below Average*

(iv) Markers such as parentheses, e.g. *not (Very High)*, *not (Very Poor)*

6.5.2 The Semantic Rule

The meaning of the composite term can be obtained if the meaning of each of the atomic terms comprising it is known. Consider, $X = hp$, where p is a primary term and h is a hedge. The linguistic function of the hedge may be explained as that of an operator, which transforms the meaning $M(p)$ into the meaning $M(hp)$ where both of them are fuzzy subsets [Zadeh, 1972 & 1973]. Thus, hedges, in a way, assist in defining the exact feeling rating of decision makers in linguistic terms.

Linguistic hedges can approximately be divided into two types:

Type 1: Hedges which can be represented as operators acting on fuzzy set such as very, plus, minus, indeed, more or less, above, below, etc.

Type 2: Hedges which require a description of how they act on the components of the operand such as essentially, technically, actually, strict, practically, regularly, virtually, etc.

The first type is easy to interpret. Contrary to Type 1, Type 2 hedges are much more complicated because they affect the components of the operand. For example, the hedge '*essentially*' has the effect of increasing the important attributes and diminishing those that are relatively unimportant. This type is not tackled here because their characterisation may require the solution of complex fuzzy algorithms and secondly they will not also be used in the present work. Mathematical models of Type 1 hedges and related concepts are discussed next.

6.5.3 Linguistic Operators and Models for Linguistic Hedges

Fuzzy sets admit a set of basic operations such as union, intersection, complement, composition, Cartesian product, concentration, and dilation [Zadeh, 1972]. Mathematical models used for linguistic operators and linguistic hedges (modifiers) include the following [Munda, 1995, pp. 103-104; Zimmermann, 1986, pp. 238-239 & 1993; Zadeh, 1972]:

6.5.3.1 Complementation

Complementation is a unary operation in the sense that it transforms a fuzzy set in U into another fuzzy set in U. More specifically, the complement of a fuzzy set $\widetilde{A}$ is denoted by $\tau\widetilde{A}$ and is defined by the relation

$$\mu_{\tau\tilde{A}}(u) = 1 - \mu_A(u), \; u \in U \quad (9)$$

6.5.3.2 Intersection

Intersection is a binary operation in the sense that it transforms a pair of fuzzy sets in U into a fuzzy set in U. More specifically, the intersection of two fuzzy sets $\widetilde{A}$ and $\widetilde{B}$ is a fuzzy set denoted by $\widetilde{A} \cap \widetilde{B}$ and defined by

$$\mu_{\tilde{A}\cap\tilde{B}}(u) = \mu_{\tilde{A}}(u) \wedge \mu_{\tilde{B}}(u), \; u \in U \quad (10)$$

where, for any real a and b, $a \wedge b$ denotes $Min(a,b)$, that is,

$$a \wedge b = a \;\; if \;\; a \le b \quad (11)$$
$$a \wedge b = b \;\; if \;\; a > b \quad (12)$$

6.5.3.3 Union

Like the intersection, the union of fuzzy sets is a binary operation. More concisely, the union of two fuzzy sets $\widetilde{A}$ and $\widetilde{B}$ is fuzzy set denoted $\widetilde{A} \cup \widetilde{B}$ or more conveniently, $\widetilde{A}$ + $\widetilde{B}$ and defined by

$$\mu_{\tilde{A}+\tilde{B}}(u) = \mu_{\tilde{A}}(u) \vee \mu_{\tilde{B}}(u), \; u \in U \quad (13)$$

where $a \vee b$ denotes $Max(a,b)$, that is

$$a \vee b = a \;\; if \;\; a \geq b \quad (14)$$
$$a \vee b = b \;\; if \;\; a < b \quad (15)$$

6.5.3.4 Product

The product of two fuzzy sets $\widetilde{A}$ and $\widetilde{B}$ is denoted by $\widetilde{A}\widetilde{B}$ and is defined by

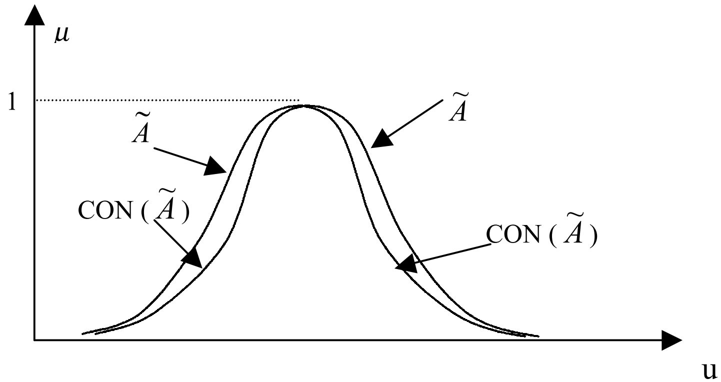
$$\mu_{\tilde{A}\tilde{B}}(u) = \mu_{\tilde{A}}(u)\mu_{\tilde{B}}(u), \; u \in U \quad (16)$$

6.5.3.5 Concentration

Concentration is a unary operation. As its name implies, the result of applying a concentrator to a fuzzy set $\widetilde{A}$ is a fuzzy subset of $\widetilde{A}$ such that the reduction in the magnitude of the grade of membership of *u* in $\widetilde{A}$ is relatively small for those *u* which have a high grade of membership in $\widetilde{A}$ and relatively large for the *u* with low membership. Thus, if one denotes the result of applying a concentrator to $\widetilde{A}$ by CON ($\widetilde{A}$), then the relation between the membership function of $\widetilde{A}$ and that of CON ($\widetilde{A}$) will typically have the appearance shown in Figure 6-1.

To be more specific, Zadeh [1972] suggested that the operation of concentration has the effect of squaring the membership function of $\widetilde{A}$. Thus,

$$\mu_{CON(\tilde{A})}(u) = \mu^2_{\tilde{A}}(u), \; u \in U \quad (17)$$

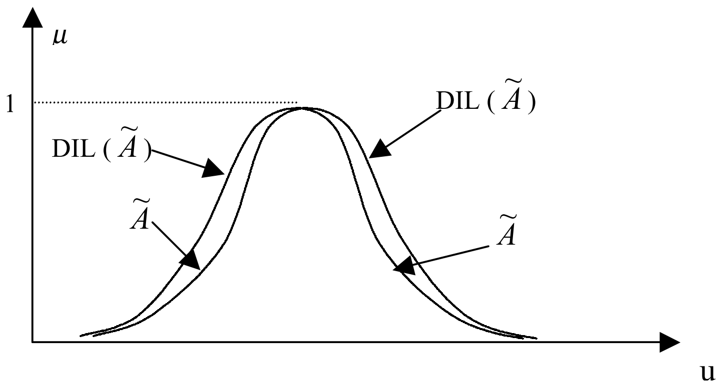


Source: Zadeh, 1972

Figure 6-1 The Effect of Concentration on a Fuzzy Set $\widetilde{A}$

6.5.3.6 Dilation

The effect of dilation is the opposite of that of concentration. Thus, the result of applying a dilator to a fuzzy set $\tilde{A}$ is a fuzzy set DIL ($\tilde{A}$) whose membership function is related to that of $\tilde{A}$ as shown in Figure 6-2.



Source: Zadeh, 1972

Figure 6-2 The Effect of Dilation on the Operand $\tilde{A}$

More specifically, the membership function of DIL ($\tilde{A}$) can be defined by

$$\mu_{DIL(\tilde{A})}(u) = \sqrt{\mu_{\tilde{A}}(u)} \quad u \in U \quad (18)$$

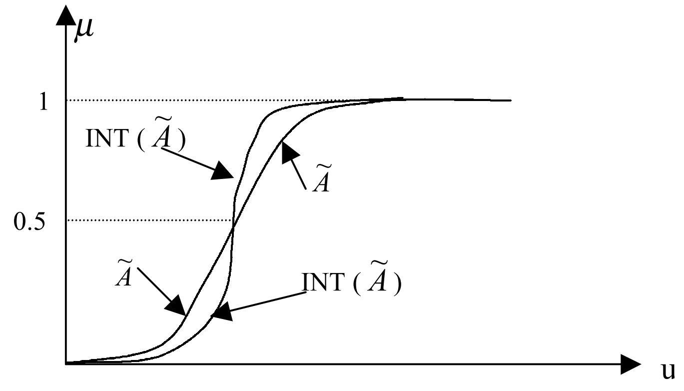
6.5.3.7 Contrast Intensification

The operation of concentration has the effect of diminishing the value of $\mu_{\tilde{A}}(u)$ for every u (except where $\mu_{\tilde{A}}(u)$=1), with the larger values of $\mu_{\tilde{A}}(u)$ diminished proportionately less than the smaller values.

The operation of contrast intensification, or simply intensification, differs from that of concentration where it increases the values of $\mu_{\tilde{A}}(u)$ which are above 0.5 and diminishes those that are below this threshold. Thus, if the result of applying a contrast intensifier INT to a fuzzy set $\tilde{A}$ is denoted by INT ($\tilde{A}$), then one can define

$$\mu_{INT(\tilde{A})}(u) = \begin{cases} 2(\mu_{\tilde{A}}^{2}(u) \ , \ for \ \ 0 \le \mu_{\tilde{A}}(u) \le 0.5 \ \ (19) \\ 1 - 2[1 - \mu_{\tilde{A}}(u)]^{2}, \ for \ \ 0.5 \le \mu_{\tilde{A}}(u) \le 1 \ \ (20) \end{cases}$$

The effect of applying this intensifier to a fuzzy set $\tilde{A}$ is shown in Figure 6-3.



Source: Zadeh, 1972

Figure 6-3 The Effect of Intensification on the Operand $\tilde{A}$

Based from the above mathematical representations, the following equations may be defined [Zadeh, 1972]. For instance, if $\tilde{A}$ is a term (a fuzzy set) then

Very $\tilde{A}$ = CON ($\tilde{A}$) (21)

More or less $\tilde{A}$ = DIL ($\tilde{A}$) (22)

Plus $\tilde{A} = (\tilde{A})^{1.25}$ (23)

Slightly $\tilde{A}$ =INT [plus $\tilde{A}$ and not (very $\tilde{A}$)] (24)

Minus $\tilde{A} = (\tilde{A})^{0.75}$ (25)

Not (Very $\tilde{A}$) =1- CON ($\tilde{A}$) (26)

However, it is cautioned here that these above formulas are just approximate (inexact) representations for membership functions of hedges and are mainly intended here to illustrate the concept rather than to provide accurate definitions of the hedges in questions. Although the proposed hedges might not have universal validity, the above equations are useful in attempting to concretise the meaning of the hedges discussed above. For example, consider, X = Very *Old*, where *Old* is the primary term and *Very* is the hedge. The linguistic function of the hedge, *Very*, can be considered as a concentrator which concentrates the meaning of the primary term, *Old*. Mathematically, this concentration can be achieved as follows. If $\mu_{M(old)}(u)$ is the membership function of the fuzzy subset *M (old)* (the meaning of *Old* where *u* is the base variable years in the universe of discourse 0 to 100 years), then the membership function of the fuzzy subset *M (Very Old)*, the meaning of *Very Old*, can be given as

$$\mu_{M(VeryOld)}(u) = \left[\mu_{M(old)}(u)\right]^2 \quad (27)$$

Another example is:

(i) The meaning associated with the linguistic variable, "*H is Small*"=Fuzzy subset of the meaning of *Small* to be suitably assigned. For instance,

$$\mu_{small}(u) = [0.3 \ \ 0.4 \ \ 0.6]$$

(ii) The meaning associated with the linguistic variable, "*H is Very Small*"=Fuzzy subset whose membership function is the square of the membership function of the meaning of '*Small*', which is a characteristic hedge operation.

$$\mu_{VerySmall}(u) = [0.09 \ \ 0.16 \ \ 0.36]$$

(iii) The meaning associated with the linguistic variable, "*H is Not Very Small*"= Fuzzy subset whose membership function is 1 minus the membership function of the meaning associated with "*H is Very Small*". This is a fuzzy *Not* operation on a relevant fuzzy subset.

$$\mu_{NotVerySmall}(u) = [0.91 \ \ 0.84 \ \ 0.64]$$

(iv) The meaning associated with the linguistic variable, " *H is Not Very Small And Not Very Large*" = Fuzzy subset whose membership function can be obtained by the intersection of the meaning associated with "*H is Not Very Small*" and the meaning associated with "*H is Not Very Large*". This is the intersection on the appropriate fuzzy subsets. For instance,

$$\mu_{L\arg e}(u) = [0.6 \ \ 0.8 \ \ 0.9]$$

$$\mu_{VeryL\arg e}(u) = [0.36 \ \ 0.64 \ \ 0.81]$$

$$\mu_{NotVeryL\arg e}(u) = [0.64 \ \ 0.36 \ \ 0.19]$$

$$\mu_{NotVerySmall \cap NotVeryL\arg e}(u) = [0.91 \ \ 0.84 \ \ 0.64] \cap [0.64 \ \ 0.36 \ \ 0.19]$$

$$\mu_{NotVerySmall \cap NotVeryL\arg e}(u) = [0.64 \ \ 0.36 \ \ 0.19]$$

(v) The meaning associated with the linguistic variable, " *H is Very Small or H is Very Large*" = Fuzzy subset whose membership function can be obtained by the union of the meaning associated with "*H is Very Small*" and the meaning associated with "*H is Very Large*". This is the union on the appropriate fuzzy subsets.

$$\mu_{VerySmall \cup VeryL\arg e}(u) = [0.09\ \ 0.16\ \ 0.36] \cup [0.36\ \ 0.64\ \ 0.81]$$

$$\mu_{VerySmall \cup VeryL\arg e}(u) = [0.36\ \ 0.64\ \ 0.81]$$

6.6 Relative Hamming Distance

The Hamming distance between two sets *A* and *B* [Kaufmann, 1975, pp. 15-18] is the quantity,

$$d(A,B) = \sum_{i=1}^{n} |\mu_A(u_i) - \mu_B(u_i)| \qquad (28)$$

where: n = number of elements considered

$\mu_A(u_i)$ = grade of membership of u_i with respect to A

$\mu_B(u_i)$ = grade of membership of u_i with respect to B

For example, assume two vectors of numbers or grades of membership, which contain only 0 (non-memberhip) and 1 (full membership):

$$\begin{array}{lccccccc} & u_1 & u_2 & u_3 & u_4 & u_5 & u_6 & u_7 \\ \mu_A(u_i) = [& 1 & 0 & 0 & 1 & 0 & 1 & 0\,] \\ \mu_B(u_i) = [& 0 & 1 & 0 & 0 & 0 & 1 & 1\,] \end{array}$$

In the above example, it can be described that u_1 is a full member of set *A* and not a member of set *B*. Similarly, u_3 is not a member for both sets *A* and *B;* u_7 is a full member of set *B* but not of set *A*.

$$d(A,B) = \sum_{i=1}^{7} |\mu_A(u_i) - \mu_B(u_i)|$$

$$d(A,B) = |1-0| + |0-1| + |0-0| + |1-0| + |0-0| + |1-1| + |0-1|$$

$$= 1+1+0+1+0+0+1 = 4$$

The relative Hamming distance,

$$\delta(A,B) = \frac{1}{n} d(A,B) \qquad (29)$$

For the example, one has

$$\delta(A,B) = \frac{d(A,B)}{7} = \frac{4}{7}$$

For the relative hamming distance, one has always

$$0 \le \delta(A,B) \le 1 \qquad (30)$$

6.7 Fuzzy Numbers & Membership Functions

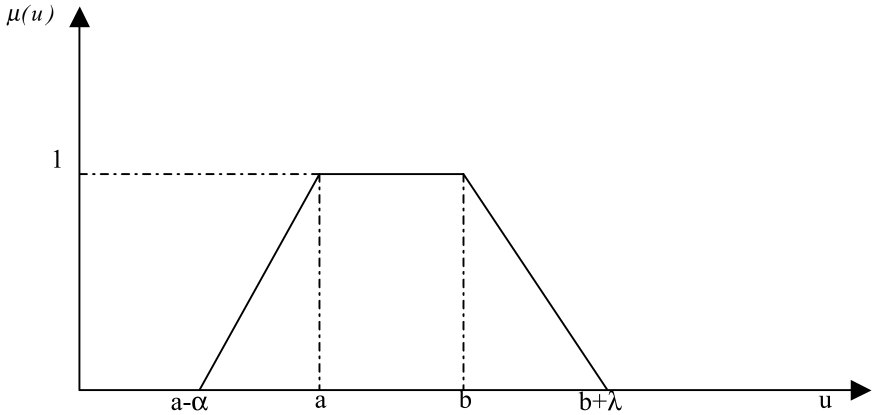
Fuzzy quantitative information has been deeply studied in the fuzzy literature by means of the notion of fuzzy numbers [Dubois & Prade, 1980; Kaufmann and Gupta, 1991].

A fuzzy number is simply a fuzzy set in the real line, which is completely defined by its membership function such as

$$\mu\ (u): R \rightarrow [0,1] \qquad (31)$$

In general, the above definition is restricted to those fuzzy numbers that are both normal and convex [Bonissone, 1982; Munda, 1995, p.102]. The requirement of convexity implies that the points of the real line with the highest membership values are clustered around a given interval (or point). This fact allows one to easily understand the semantics of a fuzzy number by looking at its distribution and to associate it with a properly descriptive syntactic label (e.g. “approximately 10”). On the other hand, the requirement of normality implies that, among the points of the real line with the highest membership value, there exists at least one that is completely compatible with the predicate associated with the fuzzy number.

A standard normal convex trapezoidal fuzzy number such as shown in Figure 6-4 can be characterised by a 4-tuple (a, b,α,λ) where [a, b] is the closed interval on which the membership function is equal to 1, α is the left-hand variation and λ is the right-hand variation. If only one point in the real line with $\mu(u)=1$ exists, the fuzzy number is called triangular fuzzy number.

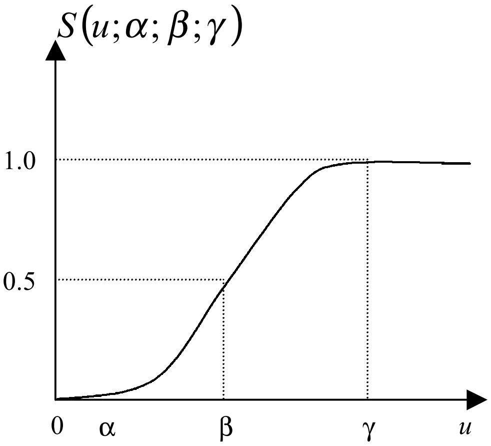


Source: Munda, 1995, p. 103

Figure 6-4 A Trapezoidal Fuzzy Number

However, Kandel [1986, pp. 6-7] proposed that in real situations, most membership functions of fuzzy numbers are non-linear such as the *S*-function and phi or pulse (π) -function. The *S*-function is described by equation (32). Figure 6-5 shows the form of *S*-function.

$$S(u;\alpha;\beta;\gamma)=\begin{cases}0, \ for \ u<\alpha \\ 2\left(\frac{u-\alpha}{\gamma-\alpha}\right)^2 \ for \ \alpha\le u\le\beta \\ 1-2\left(\frac{\gamma-u}{\gamma-\alpha}\right)^2 \ for \ \beta\le u\le\gamma \\ 1 \ for \ u\ge\gamma\end{cases} \qquad (32)$$



Source: Kandel, 1986, pp.6-7

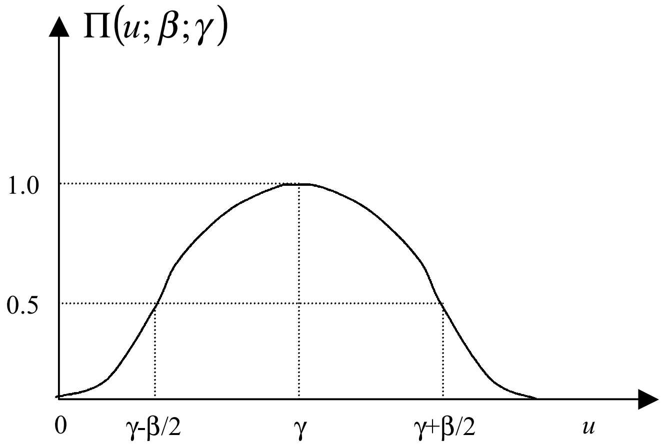
Figure 6-5 The form of S-function

In $S(u;\alpha;\beta;\gamma)$, u is specific numerical element in the universe of discourse, U and the parameter β, β=(α+γ)/2, is the crossover point, α is the point in U that the grade of membership is equal to 0 while γ is the point at which the grade of membership is equal to 1.0.

The phi-function is described by equation (33). Figure 6-6 shows the form of *phi*-function.

$$\Pi(u;\beta;\gamma)=\begin{cases}S\left(u;\gamma-\beta;\gamma-\frac{\beta}{2};y\right) \ for \ u\le\gamma \\ 1-S\left(u;\gamma;\gamma+\frac{\beta}{2};\gamma+\beta\right) \ for \ u\ge\gamma\end{cases} \qquad (33)$$

In $\Pi(u;\beta;\gamma)$, β is the bandwidth, that is, the separation between the crossover points of π, while γ is the point at which π is unity. Crossover points are the points in U at which the grade of membership, π = 0.5.



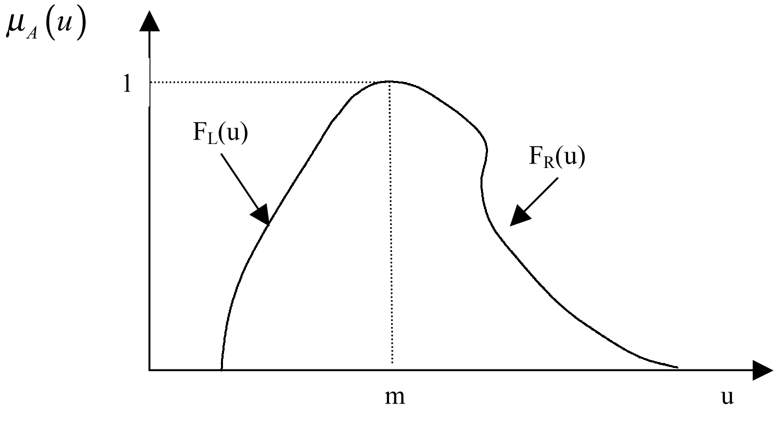
Source: Kandel, 1986, pp.6-7

Figure 6-6 The form of π-function

Moreover, a more general type of fuzzy number is the L-R fuzzy number which is shown in Figure 6-7. It is defined as follows [Munda, 1995]:

$$\mu_A(u) = \begin{cases} F_L(u-m)/\alpha & if \;\; -\infty < u < m, \; \alpha > 0 \\ 1 \;\; if \;\; u = m \\ F_R(u-m)/\lambda & if \;\; m < u < +\infty, \lambda > 0 \end{cases} \tag{34}$$

where m, α,λ are the "middle" value, the left-hand and the right-hand variation, respectively. F_L (u) is a monotonically increasing function and F_R (u), not necessarily symmetric to F_L (u), is a monotonically decreasing function. If there exists a closed interval at which the grade of membership is equal to 1, then the fuzzy number is considered as flat-type.



Source: Munda, 1995, p. 103

Figure 6-7 A L-R Fuzzy Number

6.8 Decision Support System and Decision Making Methodologies

A decision support system (DSS) is a computer-based information system that helps a manager in making key decisions and thereby improves the effectiveness of the manager's problem solving process [Mittra, 1986, pp. 4-9]. Usually, DSS caters to the strategic, tactical and operational levels of management in a company. DSS has originally four primary characteristics: (1) it helps managers mostly at the upper levels, (2) it is flexible and responds quickly to manager's questions, (3) it provides "what if" scenarios, and (4) it considers decision-making styles of managers.

Decision-making may be characterised as a process of choosing or selecting "sufficiently good" alternative(s) or course(s) of action or strategies from a set of alternatives to attain goal or goals [Ribeiro, 1996; Fitzgerald et al., 1981, p. 150; Starr, 1963, p.2]. In the past, the field of operations research used to formalise decision-making problems as follows:

- a well defined set A of feasible alternatives;
- a criterion defined on A reflecting the preferences of the decision-maker precisely; and
- a well formulated mathematical problem:

  e.g. to find a^* in A such as

  $$g(a^*) \geq g(a) \qquad \forall a \in A \tag{35}$$

  where g is a real valued function defined in A.

The choice of a^* represents the optimum decision, because a^* is better than all other alternatives in A.

6.8.1 Multi-criteria Decision Making (MCDM) Approaches

Many problems in our society are multi-dimensional in nature such as in the case of evaluation of public plans or projects where a broad set of criteria are needed to be considered. These criteria can be different in nature: private economic (investment costs, rate of return), socio-economic (employment, income distribution), environmental (pollution, deterioration of natural resources), energy (use of energy, technological innovation) and so forth. Multicriteria evaluation can be considered as the evolution of the theory explained briefly in the preceding section.

By and large, a multicriteria model presents the following aspects:

1. There is no solution optimising all the criteria at the same time and therefore the decision-maker has to find compromise solutions.

2. The relations of preference and indifference are not enough in this approach, because when an action is better than another one for some criteria, it is usually worse for others, so that many pairs of actions remain incomparable with respect to dominance relation.

In multi-criteria decision-making, one generally assumes that a decision-maker either prefers one or the other or is indifferent about the alternatives under consideration and also with the assumption that the data needed are readily available [Keeney and Raiffa, 1976; Hwang and Yoon, 1981]. As Roy [1990a, 1990b] puts it, the principal aim in multiple criteria decision aid (MCDA) is not to discover a solution, but to construct or create something which is viewed as liable to help "an actor taking part in a decision process either to shape, and/or argue, and/or transform his preferences, or to make a decision in conformity with his goals. Some of the common multi-criteria methodologies are discussed in subsequent sections.

6.8.1.1 Utility Theory Approaches

6.8.1.1.1 Multiattribute Utility Theory (MAUT)

This theory is based on the hypothesis that in any decision problem there exists a real valued function *UF* defined on the set *A* of feasible actions, which the decision maker wishes, consciously or not, to examine. This function aggregates the different criteria taken into consideration, so that the problem can be modelled such as in equation (36).

$$\max UF(g_i(a)): \quad a \in A \tag{36}$$

where $UF(g_i(a))$ is a utility function aggregating the *m* criteria (therefore a multicriteria problem is replaced by a monocriterion one). The role of the analyst is to determine this function. The most usual functions are the linear or the multiplicative form [Bell, Keeney & Raiffa, 1977].

6.8.1.1.2 The Analytic Hierarchy Process (AHP)

This method has been widely applied and a detailed explanation of the method can be found in several resources [Saaty,1980; Saaty and Kearns, 1985] and a good selection of case studies in Golden [1989]. The AHP structures the decision problem in levels, which correspond to one's understanding of the situation: goals, criteria, sub-criteria, and alternatives. By breaking the problem into levels, the decision-maker can focus on smaller sets of decisions. The AHP is based on 4 axioms:

1. Given any two alternatives (or sub-criteria), the decision-maker is able to provide a pairwise comparison of these alternatives under any criterion on a ratio scale, which is reciprocal.

2. When comparing any two alternatives, the decision-maker never judges one to be infinitely better than another under any criterion.
3. One can formulate the decision problem as hierarchy.
4. All criteria and alternatives that impact a decision-problem are represented in the hierarchy.

For almost three decades, AHP has been applied to numerous decision problems such as corporate planning problems and problems concerned with marketing strategy, energy policy, project selection, budget allocation, and so on. However, while many of the applications are related to socio-economic decision making, relatively few have been reported in the area of manufacturing or production systems decisions [Cambron & Evans, 1991; Wabalickis, 1988].

The strength of the AHP approach lies in its ability to hierarchically structure a complex, multi-attribute, multi-period problem. It purports to provide a comprehensive structure, representing a decision maker’s rational, irrational and intuitive judgements, which need not be consistent or transitive, into the decision process. The degree of consistency of a decision maker’s judgments is calculated in the AHP process [Saaty, 1980; Wabalickis, 1988].

However, in executing the AHP algorithm, the decision maker is required to construct a set of pairwise comparison matrices of integer judgments of the lower level alternatives, comparing each alternative to all other ones at the same level of hierarchy, based on their affect on each element at the higher level of the hierarchy. Thus, in applying AHP, the decision maker is required to provide numerical estimates (integer value judgments), which forces an individual to operate in a mode which requires more mental effort than that required for less precise verbal statements.

6.8.1.1.3 Utility Theory Approaches to Qualitative Multicriteria Evaluation

In multicriteria evaluation theory, a clear distinction is made between quantitative and qualitative methods. Essentially, there are two approaches for dealing with qualitative information: a direct and an indirect one [Nijkamp, Rietveld & Voogd, 1990]. In the direct approach, qualitative information is used directly in a qualitative evaluation method. In the indirect approach, qualitative information is first transformed into cardinal and then, one of the existing quantitative methods is used. Cardinalisation is especially attractive in the case of available information of a “mixed type” (both qualitative and quantitative data). In this case, the application of a direct method would usually imply that only the qualitative contents of all available (quantitative and qualitative) information are used, which would give rise to an inefficient use of this. In the indirect approach, this loss of information is avoided. The question is of course, whether there is a sufficient basis for the application of a certain cardinalisation scheme. Two examples of cardinalisation of a qualitative evaluation matrix are the expected value method and multidimensional scaling techniques [Munda, 1995, pp. 74-77].

6.8.1.2 Outranking Methods

This approach is based on what Roy calls "fundamental partial comparability axiom" [Roy, Present & Silhol, 1986]. According to this axiom, preferences can be modelled by means of four binary relations **I** (indifference), **P** (strict preference), **Q** (large preference), and **R** (incomparability).

By means of the relation of large preference, all the other relations can be obtained:

- $aPb \Leftrightarrow aQb \quad and \quad not\, bQa$
- $aIb \Leftrightarrow aQb \quad and \quad bQa$
- $aRb \Leftrightarrow not \quad aQb \quad and \quad not\, bQa$

In order to avoid giving a discriminating role to differences that are scarcely significant, indifference and preference threshold are introduced. A criterion *g* is a pseudo-criterion if there exist two-threshold functions *q (g)* (indifference threshold) and *s (g)* (threshold of presumed preference) such as $g(a) \geq g(b)$:

$$g(a) > g(b) + s\left(g\left(b\right)\right) \Leftrightarrow aPb \qquad (37)$$

$$g\left(b\right) + q\left(g\left(b\right)\right) \leq g\left(a\right) \leq g\left(b\right) + s\left(g\left(b\right)\right) \Leftrightarrow aQb \quad (38)$$

$$g\left(b\right) \leq g\left(a\right) \leq g\left(b\right) + q\left(g\left(b\right)\right) \Rightarrow aIb \qquad (39)$$

In order to avoid some inconsistencies, the threshold functions must satisfy the following conditions:

$$g \geq g' \Rightarrow g + q\left(g\right) \geq g' + q\left(g'\right) \;\; and \;\; g + s\left(g\right) \geq g' + s(g') \quad (40)$$

$$s\left(g\right) \geq q\left(g\right) \;\; for \;\; all \;\; g \qquad (41)$$

Furthermore, the first outranking approaches developed were the ELECTRE methods, developed by Roy and his collaborator [Roy, 1990b]. Nowadays different MCDA methods belonging to this family are available in the literature. Some of these are PROMETHEE [Brans, Mareschal & Vincke, 1986], PCCA (Pairwise Criterion Comparison Approach) [Matarazzo, 1991], PRAGMA [Matarazzo, 1988], CORTESIA by Giarlotta [Munda, 1995], IDRA by Greco [Munda, 1995]. Outranking approaches to qualitative multicriteria evaluation are ORESTE [Pastijn & Leysen, 1989] and MELCHIOR by Leclercq [Munda, 1995].

6.8.1.3 The Lexicographic Model

This is the model used to put in order the words in a dictionary, the first letter playing the role of the first criterion, the second letter, the second criterion, and so on. To use the model, the decision maker must give a total strict order on the criteria, such as,

$$1>2>\ldots>i>\ldots>m \qquad (42)$$

where g_1 would be the most important criterion and g_m the least important. In the lexicographic model, all actions are first ranked by means of the first criterion, then if some indifferent actions exist, these are further explored by means of the second criterion, and so on. Lexicographic orders usually lead to a straightforward selection of the most preferred alternative, however, most of the information collected on alternatives will not play a role in the choice process [Munda, 1995, p.82].

6.8.1.4 Ideal Point Approaches

Ackoff [1978] writes: "An ultimately desired outcome is called an "ideal". If one formulates a problem in terms of approaching an ideal solution, one minimises the changes of overlooking relevant consequences in decision-making. Seeking the ideal is the best way to open and stimulate the mind to creative activity". Briefly, the philosophy underlying the multicriteria methods based on ideal point concepts can be synthesised as follows [Yu, 1985; Zeleny, 1982]. Multicriteria problems are characterised by conflicts because of the perceived absence of a prominent alternative. Therefore, the only way to dissolve conflicts is to find or invent the ideal point. The only way to decrease the intensity of conflict is to find or generate alternative, which are close as possible to the ideal point. Coombs [1958] assumes that there is an ideal level of attributes for objects of choice and that the decision-maker's utilities decrease monotically on both sides of this ideal point. He shows that probabilities of choice depend on whether compared alternatives lie on the same side of the ideal or on the other. The ideal point procedures are characterised by the axiom of choice that states that alternatives that are closer to the ideal are preferred to those that are farther away. To be as close as possible to the perceived ideal is the rationale of human choice.

One of the traditional ideal point approaches is to compute the "distance" of each action from the ideal point and then rank them in terms of their closeness to the ideal. One problem related to this approach is that each action is considered completely independent from the set of all the other actions. The assumption here is that humans compare each action with the ideal rather than among themselves.

6.8.1.5 Aspiration Levels Models

Aspiration levels (or goals) express the decision-maker's ideas about the desired outcomes of the decision in terms of a certain level to be aimed at for each criterion or objective. There is a close link between the concept of aspiration level and the theory of satisfying behaviour [Simon, 1983].

The usual way in which aspiration levels are treated is by means of goal programming [Spronk, 1981]. An advantage of goal programming is that it always provides a solution, even if none of the goals are realisable, provided that the feasible region is non-empty. This is possible by using deviational variables, which show whether the goals are attained or not. In the latter case, they measure the distance between the realised and aspired levels.

An approach that can be regarded as a generalisation of goal programming and ideal point techniques is the “achievement scalarising functions” method [Wierzbicki, 1982]. The main idea is constructing a mathematical basis for satisfying decision making by introducing the wishes of the decision maker as a basic a priori information in the form of aspiration levels (reference points). Achievement scalarising functions can be considered as a modification of traditional utility functions.

6.8.2 Fuzzy Based Decision Making

The multicriteria approaches discussed in the previous section are suitable to account conflictual, multidimensional and incommensurable decisions. However, in reality, the decision maker makes a selection among alternatives based on imprecise and incomplete information such as in the case of product design decisions at the early stage. Comparing design options or even requirements at the early stage of product development is problematic because of lack of design information or of the subjectivity of the available information. A multicriteria decision making methodology that accounts this ambiguity should be adopted such as fuzzy based decision making methods.

A fuzzy based decision support system is a type of decision support system that employs data that are of fuzzy or uncertain in nature, or specifically use fuzzy linguistic variables, to aid decision-making. Decision-making methods using fuzzy set theory have recently gained acceptance because of their capabilities in handling the impreciseness that is common in system specifications, states, and alternative ratings. Chen and Klein [1997] suggested that imprecision may come from a variety of sources such as: (1) unquantifiable information, (2) incomplete information, (3) nonobtainable information, and (4) partial ignorance. Bellman & Zadeh [1970] reported the first decision model where goals and constraints are treated as fuzzy sets.

Fuzzy multi-criteria decision problems can be classified in two general categories [Ribeiro, 1996; Chen and Hwang, 1992]. These are:

1. Fuzzy multiple objective decision making (FMODM); and

2. Fuzzy multiple attribute decision-making (FMADM).

The first category (FMODM) consists of a set of conflicting goals or objectives that usually are difficult to achieve simultaneously. FMODM deals with problems where the alternatives are not pre-defined, so the decision maker has to select the more promising alternative facing the quantity of limited resources available. Resources, objectives and coefficients can all have some form of fuzziness. In the second category (FMADM), the alternatives are pre-determined and known. The decision-maker has to select or prioritise or rank a finite number of alternative actions by evaluating a group of predetermined criteria. The choice of alternatives is performed based on their imprecise attributes classification. In general FMADM has to satisfy a unique goal, however, it can be of two types [Simoes-Marques, Ribeiro & Gamiero-Marquez, 2000]: (1) select an alternative presenting the attributes with best characteristics, or (2) classify the alternatives based on a role model. The FMADM can be considered as a qualitative approach due to the existence of criteria/attribute subjectivity and fuzziness. This approach requires information about the preference among the values that an attribute could assume, as well as the preference across the existing attributes. The FMADM methods have two main phases: (1) the rating of each alternative by aggregation of the degree of satisfaction for all criteria, per decision alternative; and (2) the ranking of the alternatives with respect to the global aggregated degree of satisfaction. For more details about decision-making, decision support systems and the FMADM methodology, see the study of Simoes-Marquez et al. [2000] for a complete list. In the present study, the concept of fuzzy multi-attribute decision-making is adopted.

6.9 Fuzzy-Related Studies

In the succeeding paragraphs, non-exhaustive review of related studies on the application of fuzzy multi-attribute or multi-objective decision making methodologies is presented chronologically. The purpose of this review is to know in what real-world decision-making problems that fuzzy logic or linguistic concepts have been applied for the past 10 years.

Evans, Wilhelm and Karwowski [1987] proposed a fuzzy decision algorithm and apply it in solving block layout design problems such as locating departments within a facility. Maeda and Murakami [1988] developed a fuzzy decision-making method for multi-objective decision problems and illustrate its application to a company choice problem. Singer [1990] described a fuzzy decision method for planning the maintenance of urban infrastructural systems consisting of a large number of subsystems when the resources available are inadequate.

Moreover, Liang and Wang [1991] developed a facility site selection algorithm based on the concepts of fuzzy set theory. This decision algorithm allows assessments of alternatives versus criteria and the importance weight in linguistic terms. The best facility site is determined from potential sites based on fuzzy suitability indices. Wilhelm et al. [1991] outlined an application of linguistic variables from the theory of fuzzy sets to support the phased implementation of a computer-integrated manufacturing strategy. Knosala and Pedrycz [1992] reported a fuzzy multi-objective decision-making method dedicated to the evaluation of design alternatives in mechanical engineering. Ibrahim and Ayyub [1992] developed a fuzzy multi-criteria risk-based ranking methodology with uncertainty evaluation and propagation for the purpose of developing inspections strategies. The methodology results in establishing priority ranking lists for components where actions need to be taken based on assessments of the probabilities of failure, resulting consequences, expected human and economic risks, and the uncertainties associated with the assessments. Maeda and Murakami [1993] proposed a fuzzy multi-criteria decision-making method for a multiple-objective problem to decide what kind of computer system should be acquired for research and education in a computer-engineering department. Wilhelm et al. [1993] developed a fuzzy linguistic variable-based algorithm for the selection of waste management technologies to implement manufacturing pollution prevention strategies. Liang and Wang [1993] proposed an algorithm that aggregates decision-makers' fuzzy assessments about criteria weightings and the suitability ratings of a robot versus various selection criteria to obtain fuzzy suitability indices. The suitability ratings are then ranked to select the most suitable robot. Oder [1994] and Oder and Rentz [1994] extended one of the energy-emission models with consideration to weak data situation and fuzzy parameters for the search of cost-efficient strategies to reduce emissions from energy conservation. They applied their developed fuzzy linear program to an energy-emission model of Lithuania.

Ghotb and Warren [1995] conducted a case study on the comparison of fuzzy decision methodology and analytic hierarchy process in applying to the question of whether to introduce or not a new information technology (IT) system into a public hospital. They reported and concluded that the results from these two methods were very similar and both were considered to be useful for approaching a complex decision in a systematic way. Liao [1996] developed a fuzzy decision making method for material selection problems in engineering design applications. Adamopoulos and Pappis [1996] utilised fuzzy linguistic approach to solve a single machine-scheduling problem, where they defined the system variables in linguistic terms. Khoo and Ho [1996] developed an approach that is centred on the application of possibility theory and fuzzy arithmetic to address the ambiguity in the input data used in the QFD methodology. Their proposed approach can handle both linguistic and crisp variables and enables the "voice of the customer" which may contain ambiguity and multiplicity of meaning to be interpreted and used for decision making.

Marimin et al. [1998] proposed improvements to pairwise group decision-making based on fuzzy preference relations in three ways. These ways include first, it extends the fuzzy preference relation representation using linguistic labels; second, it modifies the computational procedures by using fuzzy sets representation and computation, and by avoiding the use of strict threshold values; and lastly, it considers fuzzy criteria of the alternatives explicitly. They applied their proposed methodology for the selection of advertising media. Temponi, Yen, and Tiao [1999] introduced a fuzzy logic-based assistance to House of Quality. They presented a method to easily determine the relationship of design requirements in the correlation matrix, which is derived from the relationship matrix of customer attributes and technical design requirements. In this way, the correlation matrix is dependent on the relationship matrix. Ghyym [1999] proposed a semi-linguistic fuzzy algorithm to obtain the fuzzy weighting values for multi-criterion, multi-alternative performance evaluation problem, with application to the aggregated estimate in the aggregation process of multi-expert judgments. He also extended the Chang/Chen method for triangular fuzzy numbers by devising a total risk attitude for a trapezoidal fuzzy number system. He applied his study on the aggregation of three-expert judgment on the containment pressure increment due to the breach of reactor pressure vessel. Wang [1999] studied QFD as a multi-criteria decision problem and proposes a new fuzzy outranking approach to prioritise design requirements recognised in QFD. He used a fuzzy logic approach because of the impreciseness and incompleteness of information and data available at the early design stage. Geldermann and Rentz [1999] and Geldermann, Spengler, and Rentz [2000] suggested a fuzzy outranking approach for environmental assessment of techniques in the iron & steel industry. In particular they have used the fuzzy PROMETHEE approach to decide which techniques are the best ones to be adopted for the establishment of emission limit values and consequently for the granting of installation permits. Kim et al. [2000] proposed fuzzy multi-criteria models to reconcile trade-offs among the various performance characteristics representing customer satisfaction as well as the inherent fuzziness. In their modelling approach, it is possible to assess separately the effects of possibility and flexibility inherent or permitted in the design process on the overall design. Simoes-Marques et al. [2000] developed a fuzzy decision support system and apply it to support equipment repair under battle conditions. Noci and Toletti [2000] conducted a comparative study between fuzzy linguistic approach and the analytic hierarchy process by applying them in the case of selecting quality-based programs in small firms. They analysed the two methods in terms of completeness of the analysis, reliability of the output, ease of use of the technique and intuitiveness of the technique. They found that the two methods are characterised by the same level of completeness and resulted to more or less similar ranking results. Both the techniques are easy to use but fuzzy linguistic approach is easier because one only need to assign some linguistic assessments to the variables considered whereas with the AHP, one has to do pairwise comparisons among the variables which represents a time-consuming analysis. Additionally, both methods are not considered intuitive by managers because of the use of matrix algebra. Hence, they concluded that it is not possible to identify which is better between these two methods. Schultmann, Schmittinger and Rentz [2001] explored the potential application of fuzzy petri nets for the modelling and simulation of the material interrelationship in a production system, which eventually provides strategies for an efficient management of mass and energy flows.

6.10 Brief Chapter Conclusion

Although there are already several studies that report the applications of fuzzy sets and systems in multicriteria decision-making, it has been established that there is no specific study conducted on the application of this method to the strategic evaluation and selection of sustainable product system improvement alternatives. The use of fuzzy multi-criteria methodology in the domain of product development could be appropriate because imprecise and incomplete design information, in addition that there are different criteria to be considered, is typically encountered at the early product design stage. This deficiency in fuzzy multi-criteria literatures is considered and studied in the next chapter. The concepts of fuzzy relations, linguistic variables, linguistic hedges, relative Hamming distance and the notion behind the “ideal point multicriteria approach”, which are explained above, will be adopted in the development of the fuzzy linguistic-based approach for the evaluation and selection of sustainable product improvement alternatives in Chapter 7.

The next succeeding chapters cover the application of the developed methodology and subsequently followed by results and discussion of the case study, by conclusion and recommendations for future research and lastly, by the summary of the dissertation.

7 Development of an Approach for the Selection of Sustainable Product System Improvement Concepts

In this chapter, the developed conceptual methodology is discussed in detail and its framework is shown in Figure 7-1. This conceptual approach is focused on how to possibly integrate environmental, quality, and cost requirements and how to employ fuzzy linguistic variables to address the imprecision and incompleteness of design data inputs at an early phase of product improvement or development.

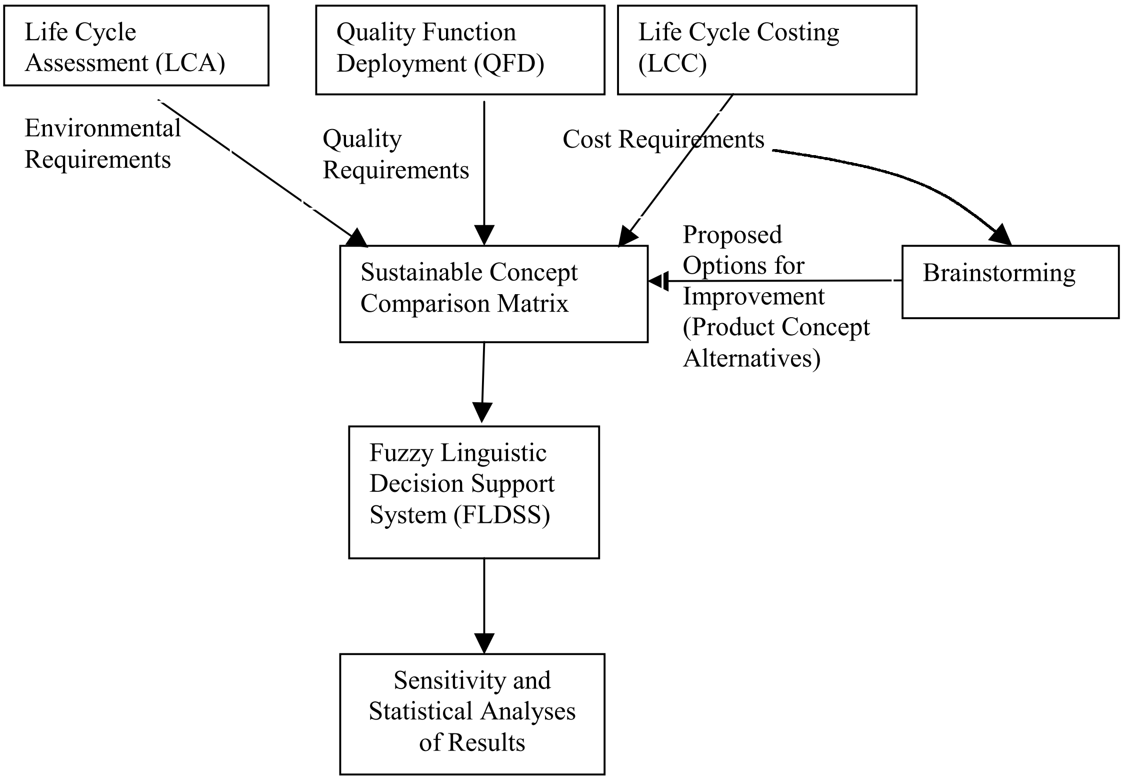


Figure 7-1 Framework of an Approach for the Evaluation and Selection of Sustainable Product System Improvement Alternatives

In Figure 7-1, the first phase involves the identification and documentation of the attributes of the baseline or reference product (usually refers to the company's existing product) with respect to environmental, cost and quality aspects. This information is obtained through the use of streamlined and/or modified LCA, QFD, and LCC methods. The environmental requirements of a reference product are synonymously defined here as "environmental impact categories" with an adjective added to it, for instance, "reduced acidification potential“. These environmental impact categories are based on the mass and energy flows using the inventory analysis and classification steps of LCA method, which in turn were obtained from the environmental life cycle data of a product. The customer quality requirements' information, on the other hand, is extracted from a modified House of Quality (HOQ) methodology. A modified HOQ procedure provides a systematic determination of relevant quality related requirements, importance of these requirements and relationships between customers' quality requirements and the product components. The cost requirements are deduced from a simplified LCC methodology.

In the second phase, the identified requirements or attributes from streamlined LCA, modified QFD and simplified LCC methods are then utilised as basis to develop alternative concepts for product system improvement. These options for system improvement could be generated through systematic methods such as group brainstorming. Next, the critical quality, environmental and cost (QEC) requirements are listed against the proposed options for product improvement in the sustainable concept comparison matrix, which is discussed in sections 7.6 and 7.7 in detail. However, before one can evaluate each sustainable improvement proposal with respect to QEC attributes, one has to estimate first the expected environmental and cost performances of the options for system improvement by analogy to the reference system. This is due to the fact that environmental and cost performances of the alternatives are not known in advance and might also be different from the reference product system.

In the third phase, basing from the estimated environmental, cost and quality performance of the alternatives for improvement, the decision maker or the product development team (as a whole) has to evaluate the importance of the QEC requirements and assess the capability of each of the proposed system improvement alternatives in meeting each QEC requirement by using defined fuzzy linguistic variables which are fully discussed in section 7.7. Fuzzy linguistic approach is employed here because of the imprecision of pertinent information and the uncertain nature of the estimated costs and emissions used at the early phase of the product development. For the purpose of selecting the optimal sustainable option for product system improvement, the product improvement alternatives are ranked eventually according to their relative hamming distances, which are calculated through the use of a fuzzy linguistic heuristic algorithm. In the final phase, sensitivity and statistical analyses are conducted to confirm the preference or ranking of alternatives established by the fuzzy linguistic methodology.

7.1 Definition of Product and Process Structures and Functional Unit

Assuming that a reference product system and its corresponding manufacturing process for sustainable improvement are already selected, defining the right functional unit and making a complete description of the product structure of the selected reference product are of crucial importance particularly in conducting life-cycle analysis. A functional unit is used as a fundamental basis for all types of comparisons between alternatives (e.g. illuminate a 25-m^2 room over a period of 20 years in a given standard for illumination). This unit covers all-important functions of the product system, and is a measure for the life cycle efficiency of a product in fulfilling the important end-user or customer requirements. This unit is closely similar to the basis used in all material and energy balances and conservation calculations in chemical process engineering. Related to the functional unit is the reference flow. This refers to the total mass of a product that is necessary to fulfil the functional unit, e.g. 12 light fittings weighing 3.5 kg each or a total of 42 kg.

In prescribing the functional unit for the reference product system, four dimensions should be taken into account:

1. functionality according to given standards or customer requirements
2. product efficiency
3. life span (should be long enough to evaluate differences in product quality, costs and environmental impacts)
4. include several functions if necessary (e.g. light and heat)

A product structure is a way to describe the product system in terms of its functions and components. Decomposition of the product system should be done to aid in the analysis of main product components, functions and specific raw materials. Normally, this is done with the help of existing product drawings and material lists, or the receipts of chemical products. If the material list (with its weight composition of different materials) is not available, then this should be gathered by weighing the different components and also by contacting the suppliers to get detailed information about material composition.

Moreover, process flow diagrams can assist in securing data about different sources of emission factors, energy usage and material consumption throughout the life cycle stages. A flowchart is recommended in order to visualise the included components and the connections between them. Other important information that may be gathered is the following:

1. origin of different materials and distribution between suppliers for important raw materials (covering more than 10% of total mass of the product)
2. transport media for the raw materials, intermediates, and final products to the end-consumer
3. fraction of recovered materials in raw material
4. data about the distribution phase, the user phase and the waste management phase.

The first three of the preceding information are normally available in the purchasing and logistics department. The fourth one is difficult to acquire but might be obtained from representatives of service, technical support and marketing departments. Examples of these information include expected lifetime of the product, maintenance and repair activities, quantity and quality of returned product and defects, recycle and repair strategies, consumers' usage and behaviour related to the product and waste management for end-product in different markets.

7.2 Life Cycle Assessment of Product Systems

Knowing the product and process structure, product's functional unit and other relevant information, an environmental life cycle assessment of the reference product could be done. In this study, comprehensive LCA is not used but rather a streamlined version is adapted with particular relevance to inventory analysis and the classification steps of LCA. Graedel [1998] suggested different methods of streamlining LCA. These are briefly covered in section 4.8.1. The idea of streamlining is adopted here to account for availability of data requirements, few days of effort rather than several months, and particularly its usability in the early stage of product design.

For the present purpose of streamlining the LCA and increasing work efficiency, the following guidelines are proposed here to simplify the data gathering of emissions, waste streams, and energy consumptions:

1. Assume no problem with regard to allocation when processes convert several raw materials into several end-products and by-products.
2. For impact categories where it is difficult to get quantitative data and thus make quantitative assessments difficult, more qualitative data should instead be gathered.
3. Interpretation and recommendation stage is not included in the LCA study.
4. Only selected environmental impacts and inventory parameters are considered.

In this work, an adaptation of the House of Ecology (HOE) developed by Halog et al. [2001] which is called here as "green house " (as shown in Figure 7-2), is used to organise the information gathered for the determination of the critical emissions and to classify the environmental emissions and consumptions into their appropriate environmental impact categories. The term "house" is used here interchangeably with the term "matrix".

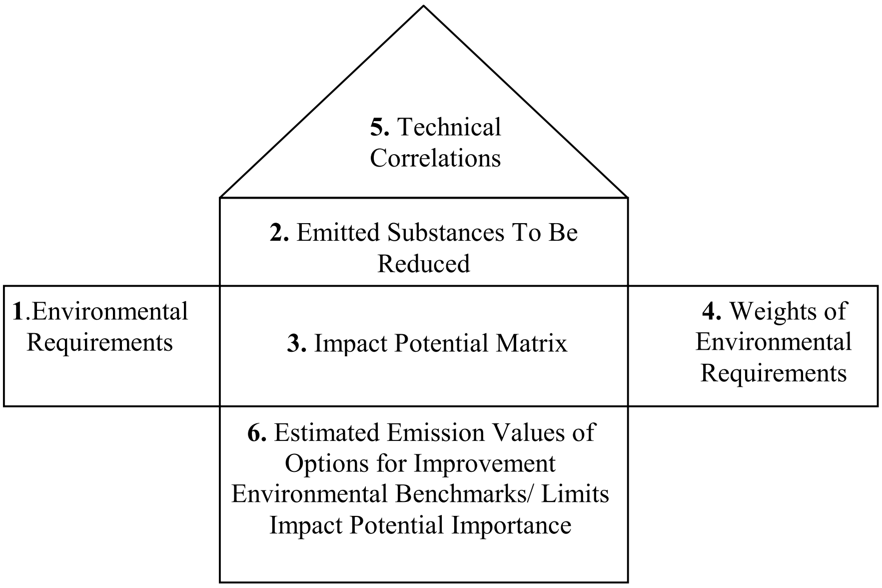


Figure 7-2 Green House or Matrix

The descriptions of the areas in the above figure are as follows:

Area 1: Environmental requirements are derived from the environmental impact categories established by inventory and classification stages of LCA. Impact categories compile the potential impacts on the environment caused by the individual emissions and consumptions and reflect environmental problems. For example, SO_x emission contributes to the impact category of acidification potential and thus the environmental requirement can be defined as “less or reduced acidification potential”;

Area 2: Emissions emitted or consumptions during the life cycle stages;

Area 3: For evaluating the relationship of emissions and environmental requirements, the impact potential matrix (relationship matrix) is described as the degree of contribution of a certain emission to a certain impact category. For example, in what degree is the impact of SO_x to the acidification requirement of the environment? The impact potential (IP) of this emission is used as measure of the degree of satisfying the requirement of less or reduced acidification and is equal to the standard values as provided in the tables given in Rentz et al. [1998] or see Appendix H for extract of these tables;

Area 4: Weights of environmental requirements are in accordance with the opinions or estimates provided by the environmental experts within the product development team;

Area 5: The triangular top portion in the above house might represent the correlation or trade-offs on the reductions among emissions and energy consumptions. This area is also difficult to determine because it requires deeper study just to know the trade-offs on the amounts of reduction among emissions and/or consumptions. In the case study presented in the next chapter, this area will not be included because the data needed are unavailable;

Area 6: The data used for the inventory analyses of the proposed alternatives are estimated by analogy (see section 5.6.2 for general explanation of estimation by analogy) by environmental experts. The target specifications are the results of the environmental benchmarking of emission or consumption values for the options considered but alternatively, emission limits for water, air, and land as provided by environmental agencies could also be used if available. The ranking of the emissions and consumptions is based on the calculation of environmental impact potential importance. Environmental impact potential importance is equal to the product of normalised weight of the environmental requirements and the normalised impact potential factor. Then, for each column, the values are added to get the impact potential importance of the emissions or consumptions to the environment, which serves as a basis for ranking. The greater the impact potential importance of the emission, the more environmentally critical it is and thus, it should be addressed immediately.

In summary, the goals of the abridged environmental life cycle assessment in the present study are to analyse and assess the environmental performance of a product system, to know at which stage of the product life cycle that environmental problems mostly arise and which of the emissions are considered critical and need to be focused first, and eventually to use the results for comparing alternatives for environmental product system improvements.

7.3 Life Cycle Cost Accounts of Product System

Normally investments in machineries and equipments are subjected to economic analyses over a long period of time, e.g. 10 years of operation. However, this is seldom or never the case with products. When buying products, the purchasing price, not the life cycle cost, remains the most applied economic criterion [Hanssen, 1997, pp.14.5].

Life cycle cost analysis is based on the same principles as in investment analysis. There is a cash flow accounting for all related activities to a given investment. However, in the present study, the LCC analysis is modified and simplified because of the following considerations. First, the analysis to be conducted is related to a specific product, which normally involves repeated buying and usage during a given time period. Second, the analysis is related to a functional unit of the product system, as in the LCA method. The functional unit and the life cycle product and process structure are thus the basis for the LCC analysis, and all cost factors are related to this unit. Third, the usual method of net present value for calculating LCC is not used here for the reason that it is only intended here to show the costs related to specific product systems in a life cycle perspective, and not to adjust to factors such as depreciation and tax systems. Depreciation is indirectly or implicitly related to net present value [Perry and Green, 1997, pp. 9.7-9.8]. If the depreciation is defined as tax allowance, then the annual taxable income is reduced by this depreciation charge which has the effect of reducing the annual amount of tax payable. If the depreciation is considered to be a manufacturing cost in the same way as labor cost or raw materials cost, then this depreciation charge is implicitly accounted in the calculation of net present value. Fourth, it is assumed here that inflation rate and rent are in balance without calculating a net present value of the life cycle cash flows.

The modified life cycle cost evaluation for the users should provide information for the product development team on which system processes and components that are more costly to the customers. Knowing these costly processes and components, improvements can be geared towards increasing the life cycle competitiveness of the producer. However, it is cautioned here that the gathering of detailed cost data and even the calculation of their estimates are difficult, if not impossible. Thus, it is more realistic to estimate the net life cycle costs for the customers based in the following main cost factors [Hanssen, 1995 and 1997]:

- Product purchasing costs
- Energy costs with different energy carriers
- Transport Costs
- Environmental control costs (e.g., hazardous waste treatment)
- Maintenance costs
- Operation costs
- Service and repair costs
- Costs related to final waste treatment of product

Yet, it is important to make a screening of the above cost factors, and focus only to those cost data, which are very relevant in the calculation of total life cycle cost. Costs that are the same across the alternatives should not be included. The expected output of this analysis is to provide cost profiles (in the form of bar graphs) of the total life cycle costs of the options for improvement, which are estimated by analogy (see section 5.6.2 for general explanation) with respect to the life cycle cost of the reference product system.

7.4 Customers' Product Quality Requirements of Reference Product System

The ultimate reason for customers to buy a product is that the product fulfils more or less well their defined needs or requirements. Thus, the important challenges for manufacturers are: (1) to identify the critical customer requirements of a product, (2) to incorporate these requirements in the product's design specification, and (3) to design the product so that it will be preferred in the market.

In the present study, the standard House of Quality (HOQ) procedure of QFD is modified and adapted to fit the current availability of data. QFD in its advanced form is a complicated methodology, however, the approach can systematically address "what are the customer needs and requirements" and the connections with "how these needs and requirements are met in a product". By using a modified and simplified version of QFD method, which is called quality matrix or house here, such as shown in Figure 7-3, valuable information about the relationships between customer requirements (voice of the customer) and the product structure (product system components) could be obtained.

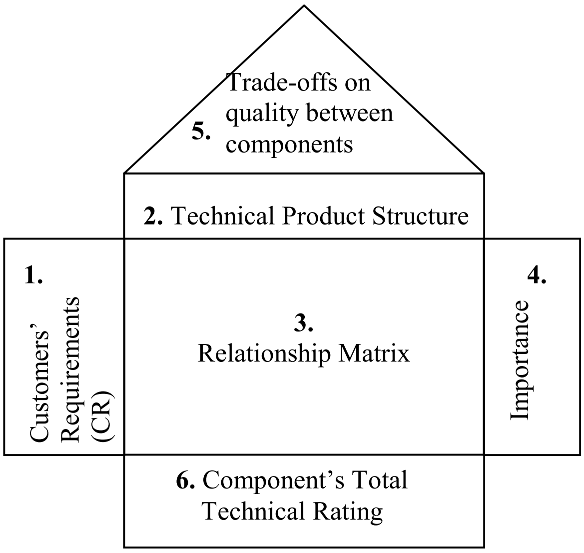


Figure 7-3 Quality House or Matrix

The descriptions of the areas in the above figure are as follows:

- *Area 1* includes the customer requirements (CR) organised into appropriate classifications. CRs are the product's requirements in customer's terms. The structure is usually determined by qualitative research such as structured interviews and surveys;
- *Area 2* refers to the product components of the reference system;

- *Area 3* is the relationship matrix. One may adopt **+, o,** and – signs to symbolise the relationship between the customers' requirements and the technical product components. The plus sign (+) means positive relation and that the quality improvement in product components and/or processes contributes positively to the satisfaction of customers' requirement. The zero (***o***) sign symbolises that there is no relationship exists or the relationship is weak. The minus sign (**-**) represents negative relation and that the quality improvement in product components and processes contributes negatively to the satisfaction of customers' requirement.

- *Area 4* provides the weights or importance of the requirements. Here, one may adopt the following rating system: 5= Critical, 3= Important, 1= Unimportant and furthermore, a rating of 4 or 2 could be used to describe the importance rating between 5 and 3, or 3 and 1 respectively.

- *Area 5*, the "roof" of the house, captures the trade-offs between the quality of various product components. Here, strong conflict is indicated by ✖. Weaker conflicts would be indicated by ×. Strong synergy would be indicated by ✔, and weaker synergy by ✓. This area is the most difficult to determine and usually left by those who are doing QFD studies because it requires deeper study just to know the trade-offs.

- *Area 6* involves the determination of components' technical ratings. This will provide information on which parts of the product structure contribute significantly to product system improvements and eventually to the satisfaction of the most important customer requirements. For the calculation of technical rating, one may replace the + *sign by* 9, *o sign with 3* and – *sign with 1* that are used in the relationship matrix so that one can get the technical rating of a product component with regard to all customers' requirements considered. This is accomplished by simply multiplying the equivalent value of the relationship between requirement and the product component and the importance value of requirement and finally adding the values in each column to get the total technical rating. Through this computation of technical rating, one can maximise the satisfaction of customers' requirements by determining those parts that require critical attention.

The most important information out of this figure is the list of customers' quality requirements that need to be included in the sustainable concept comparison matrix or house, which is described in Figure 7-4. A specific example of this figure with regard to the case study of the present work is shown in Table 8-2.

7.5 Generation of Proposed Alternatives for System Improvement

After securing the information on the important environmental, quality and cost issues of the reference product system, the cross-functional product development team should systematically search for ideas to improve the baseline product system in a sustainable basis. There are many techniques available for the team to help stimulate the creative aspects of design work such as brain writing, Delphi method, simulation, role playing and brainstorming [Nadler & Hibino, 1994; Rochford, 1991; Urban et al., 1993, 118-127]. In this work, brainstorming is used because it is a common tool for doing creative tasks in manufacturing organisations, such as developing products, overhauling business systems and improving manufacturing. It can also be very effective for generating quickly a large number of ideas as long as people are stimulated.

To assist members of the product development team to conduct a brainstorming process systematically, the following steps are recommended.

1. Participants in a project team (with cross-functional backgrounds and expertise) write their ideas in a notebook during the period between the project meeting (when the targets were established and areas for improvements defined), and the first idea generation meeting;

2. Brainstorming should be used in the project meeting to generate as many ideas as possible and criticisms should be avoided. The brainstorming technique could start systematically by using the listed possible strategies based from all notebooks of participating members.

3. Pre-screening of the ideas should be done by the project team, for instance, based on the following categories:

- concepts which are easily implemented for improvements of the existing product;

- concepts which are possible to implement in a new product but need technological research for verification; and

- concepts with great potential but need significant research for verification and eventual implementation of ideas which are impossible to implement or of no interest at all.

Hanssen [1997 & 1995] proposed a list of four main strategies including its sub-strategies that can be used for product system improvements. This recommended list of strategies could be used as a reference for a creative problem solving by a project team to bring up as many ideas as possible regarding product system improvements. These different strategies are presented in Appendix *G*.

7.6 Sustainable Concept Comparison House or Matrix

After knowing the quality, environmental and cost requirements including the proposed concepts for product system improvement, a "sustainable concept comparison house" such as in Figure 7-4 can be constructed. This house aids to facilitate the conduct in making an evaluation of the options for improvement with respect to critical environmental, quality and cost criteria and to finally choose the optimal or best sustainable option for system improvement. The term "house" and "matrix" are used here interchangeably. The idea of developing this house is adapted from the House of Quality concept. However, before proceeding to evaluate the sustainable options, it is better to have rough estimates of the emissions, consumptions and cost profiles of the proposed product improvement alternatives so that one has a basis in rating linguistically the capability of each option to meet each requirement using fuzzy linguistic values. This estimation by analogy can be done using the environmental and cost profiles of baseline product system as reference.

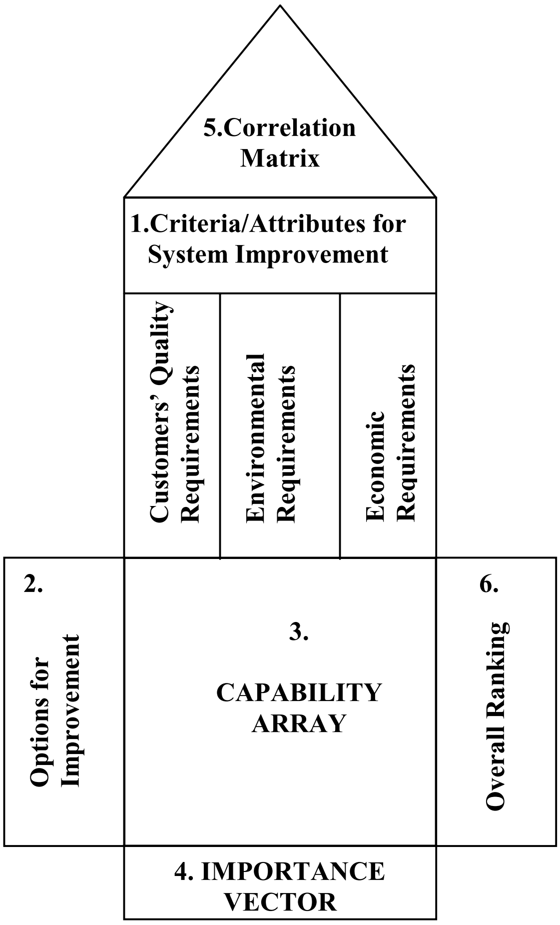


Figure 7-4 Sustainable Concept Comparison Matrix or House

The descriptions of the areas in Figure 7-4 are the following:

- **Area 1** lists the quality, environmental and cost attributes or requirements that were extracted or deduced from the green matrix (LCA), quality matrix (QFD) and cost profiles (LCC);

- **Area 2** provides the options for sustainable product improvement that were generated by brainstorming process;

- **Area 3** is the capability array, which represents the effectiveness of an option for improvement to meet each of the environmental, quality and economic requirements considered. The product development team should make intelligent evaluations through the use of linguistic values of fuzzy linguistic variable – *CAPABILITY-* while basing them from the estimates for cost and environmental profiles of the alternatives. This fuzzy linguistic variable "Capability" is explained in detail in section 7.7 below. For example, how capable is option 1 to satisfy the environmental requirement of "reduced acidification " of the product system?

- **Area 4** is the importance vector, which provides the weights of the critical requirements with the use of linguistic values of fuzzy linguistic variable – *IMPORTANCE*. This is also discussed in detail in section 7.7. The weights are assumed to be provided by the decision maker or the product development team.

- **Area 5** is the triangular shaped-correlation matrix, which refers to the trade-offs or synergy between QEC requirements for the product system improvement. Here, one may use ✖ to indicate strong conflict, × for weaker conflicts, ✔ for strong synergy and ✓ weaker synergy. This area is interesting because this will provide the conflicts or synergies between requirements, which is one of the characteristics of problems solved by multi-criteria methodologies. However, in the application section of this methodology, this would not be included because the needed data for this aspect is not available.

- **Area 6** gives the overall ranking of the options for improvement either linguistically or by calculating the relative hamming distance using a fuzzy linguistic algorithm discussed below.

7.7 Evaluation and Selection of Options for Improvement Using Fuzzy Linguistic Approach

One difficulty encountered in the present work is the lack of precise information about the performance of proposed product system improvement concepts at the early phase of product development. This shortcoming has been clearly pointed out in the previous chapters. This inadequate information in the idea phase, where most of design aspects with respect to cost, quality and environmental requirements are considered, could affect the decision on which option for improvement to be pursued or further deployed in succeeding product development stages. It is advisable then that improvement in the reliability and quantity of information to support decision-making is necessary. However, to lessen the dependency for accurate quantitative information in assessing the options for product improvement in this work and also since the options for improvement are still concepts to be implemented, it is proposed in the present study that a qualitative or semi-quantitative approach such as fuzzy linguistic method (that can handle imprecision involved in data inputs, information, and estimates) should be used.

As the previous chapter explained, fuzzy linguistic models permit the translation of linguistic terms into numerical ones. In this study, fuzzy linguistic models deal quantitatively with imprecision in the expression of the *Importance* of each requirement or attribute strategic to the firm's plan for sustainability and the *Capability* of each option for improvement in addressing each strategic attribute. That is, the *Capability*, or *Effectiveness*, of each alternative in achieving each strategic requirement for sustainability is assessed in terms of natural language instead of using surrogate measures such as quantitative weighting factors, scores or estimated costs used in the LCA, QFD and LCC analyses above. Use of natural language assessment is also suitable because Zimmer [1983] asserted that human decision makers are unsuccessful in making quantitative predictions, whereas they are comparatively efficient in qualitative forecasting. Further, people are more prone to interference from biasing tendencies if they are forced to provide numerical estimates since the elicitation of numerical estimates forces an individual to operate in a mode which requires more mental work than that required for less precise verbal statements [Karwowski & Mital, 1986].

Assuming that one has already a complete sustainable concept comparison house or matrix such as Table 8-7 for the case study, the problem now is how the most suitable and optimal option for sustainable product system improvement from among those available will be selected. In applying a fuzzy linguistic based approach to the evaluation of options for improvement for design for sustainability, two fuzzy linguistic variables need to be defined:

X =linguistic variable which is called " ***Importance*****",** and

Y = linguistic variable which is called " ***Capability***"

A linguistic variable is a variable that admits as value words or sentences of a natural language, which can be represented as fuzzy sets. To understand easily the notion of a linguistic variable, regard it either as a variable whose numerical values are fuzzy numbers or as a variable where the range of which is not defined by numerical values but by linguistic terms. Discussion on the basic concepts of fuzzy linguistic variables can be found in section 6.5. The use of the defined two linguistic variables allows the design engineer, analyst, decision maker or the product development team to specify the ***Importance*** associated with the criteria or attribute, i $(i = 1,\ldots m)$ common to all options for improvement, and the ***Capability*** of each option (product improvement alternative), j $(j=1,\ldots n)$ to meet each criterion or attribute, i, for the eventual sustainability goal of the organisation. For example, option 2 in Table 8-7 (substitute the alloy of aluminium/zinc with black iron) is *above* *average* in its ability to meet the requirement of "reduced acidification potential", which is *very important* criterion in accomplishing the company's strategy for sustainable product development. In the preceding sentence, the term *above average* is a linguistic value, *y*, of the fuzzy linguistic variable ***CAPABILITY***, and the term *very important* is a linguistic value, *x*, of the fuzzy linguistic variable ***IMPORTANCE***.

7.7.1 Generation of Membership Functions

Before proceeding to relate the linguistic variables *X* and *Y*, let us explore the possibilities in generating membership functions. Suppose *M (x)* or *M (y)* is defined as a semantic rule (see section 6.5.2 for further explanation) for associating a meaning of each linguistic value (e.g. critical or superior) for linguistic variable *X or Y* respectively, and is, itself, a fuzzy subset of the entire set (the universe of discourse), *U=[0,1]*, written as

$$M(x)=\left\{x,\mu_{M(x)}(u_x)\middle|u_x\in U\right\} \quad (43)$$

$$M(y)=\left\{y,\mu_{M(y)}(u_y)\middle|u_y\in U\right\} \quad (44)$$

where:

$\mu_{M(x)}(u_x)$= membership function (or grade of membership for a specific value of u_x) of u_x in *M(x)* ; For example, $\mu_{M(critical)}(0.1) = 0;$

$\mu_{M(x)}(u_x)$= membership function (or grade of membership for a specific value of u_y) of u_y in *M(y)* ; For example, $\mu_{M\ (superior)}(0.2) =0;$

u_x = specific numerical value in *U* with respect to *x* (e.g. 0.1)

u_y=specific numerical value in *U* with respect to *y* (e.g. 0.2)

For example, $M(critical)=\left\{critical,\mu_{M(critical)}(0.1)\middle|0.1\in U\right\}$.

At present, there is not yet a well-established standard set of membership functions or even method for generating membership functions. Several researchers nowadays are currently using trapezoidal or triangular membership functions for the sole purpose of reducing the amount of computational effort and for ease for data acquisition. However, in real situations, most membership functions of fuzzy numbers are non-linear [Kandel, 1986, pp.6-7; Karwowski, Marek & Ostaszewski, 1989, pp. 141-154]. Kandel [1986, p.6] suggested that it is convenient to express the membership function of a fuzzy subset of the real line in terms of a non-linear standard function, whose parameters may be adjusted to fit a specified membership function in an approximate fashion. Two such standard non-linear functions are the *S*-function and π-function, which are briefly covered in section 6.7. For instance, in Table

7-1 below, the membership function for x = *critical* is a case of a discretised S-function, while that for x = *important* is an example of a discretised π-function.

The primary linguistic values of X (e.g. critical*, important, unimportant*) and of Y (e.g. superior, average, poor) together with their membership functions in discretised form (or grades of membership at selected u_x or $u_y \in [0,1]$), are presented in Tables 7-1 and 7-2 below. These primary linguistic values as well as the numerical values of u_x and u_y were selected arbitrarily and are not intended to be rigorous specifications for every analysis. For example, in Table 7-1, the membership function of u_x in the linguistic value, *Critical*, is expressed in terms of 1 X 11 row vector of numbers or grades of membership such as shown in equation (45).

$$\mu_{M(Critical)}(u_x) = [0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.05\ 0.15\ 0.80\ 1.0] \qquad (45)$$

Table 7-1 Compatibility (Membership) Functions of Primary Linguistic Values for X= Importance

Linguistic Value, x	**Selected values of u_x**										
	0.0	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**1.0**
Critical	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.15	0.80	1.0
Important	0.0	0.10	0.25	0.75	0.90	1.0	0.90	0.75	0.25	0.10	0.0
Unimportant	1.0	0.80	0.40	0.20	0.05	0.0	0.0	0.0	0.0	0.0	0.0

Similarly, in Table 7-2, the membership function of u_y in the linguistic value, *Superior*, is expressed in terms of 1 X 11 row vector of numbers or grades of membership such as shown in equation (46).

$$\mu_{M(Superior)}(u_y) = [0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.0\ 0.10\ 0.30\ 0.90\ 1.0] \qquad (46)$$

Table 7-2 Compatibility (Membership) Functions of Primary Linguistic Values for Y= Capability

Linguistic value, y	**Selected Values of u_y**										
	0.0	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**1.0**
Superior	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.30	0.90	1.0
Average	0.0	0.05	0.10	0.35	0.80	1.0	0.80	0.35	0.10	0.05	0.0
Poor	1.0	0.80	0.40	0.20	0.05	0.0	0.0	0.0	0.0	0.0	0.0

In addition to the defined primary linguistic values of X and Y presented in Tables 7-1 and 7-2, it is assumed that negation, or *'not'*, and connectives (e.g. '*and'* and *'or')*; and linguistic hedges (e.g., *indeed, very, more or less, above*) exist. These linguistic operators form new linguistic values from the primary linguistic values (or operands), which are called here as composite linguistic terms. For example, *very important* is a result from the composition of the *hedge "very"* and the primary linguistic value *"important"*.

Membership functions of composite linguistic terms may be constructed from the primary linguistic values with the use of hedges, connectives, and operators that might include the approximate formulas as shown below. These equations are based from the concepts of dilation, concentration, complementation and contrast intensification, which were introduced in the works of Zadeh [1976 & 1975], which was discussed in section 6.5.3 in detail. Nevertheless, these equations do not necessary have universal validity and should not be followed in all situations.

$$x = \mathit{Indeed\ \ Critical};\ \mu_{M(x)}(u_x) = \begin{cases} 2\left(\mu_{M(Critical)}\right)^2 \ \ \mathit{for}\ \ 0 \le \mu_{M(Critical)} \le 0.5 \\ 1-2\left(1-\mu_{M(Critical)}\right)^2 \ \ \mathit{for}\ \ 0.5 < \mu_{M(Critical)} \le 1.0 \end{cases} \tag{47}$$

$$x = \mathit{More\ \ or\ \ less\ \ Critical};\ \mu_{M(x)}(u_x) = \left(\mu_{M(Critical)}\right)^{0.5},\ \mathit{for}\ \ 0 \le \mu_{M(Critical)} \le 1.0 \tag{48}$$

$$x = \mathit{Very}\ \ \mathit{Important};\ \mu_{M(x)}(u_x) = \left(\mu_{M(Important)}\right)^2,\ \mathit{for}\ \ 0 \le \mu_{M(Important)} \le 1.0 \tag{49}$$

$$x = \mathit{More\ \ or\ \ less}\ \ \mathit{Important},\ \mu_{M(x)}(u_x) = \left(\mu_{M(Important)}\right)^{0.5},\ \mathit{for}\ \ 0 \le \mu_{M(Important)} \le 1.0 \tag{50}$$

$$x = \mathit{Not\ \ important},\ \mu_{M(x)}(u_x) = 1-\mu_{M(Important)}\ ,\mathit{for}\ \ 0 \le \mu_{M(Important)} \le 1.0 \tag{51}$$

$$y = \mathit{Indeed\ \ Superior},\ \mu_{M(y)}(u_y) = \begin{cases} 2\left(\mu_{M(Superior)}\right)^2,\ \mathit{for}\ \ 0 \le \mu_{M(Superior)} \le 0.5 & (52) \\ 1-2\left(1-\mu_{M(Superior)}\right)^2,\ \mathit{for}\ \ 0.5 < \mu_{M(Superior)} \le 1.0 & (53) \end{cases}$$

$$y = \mathit{More\ \ or\ \ less\ \ Superior},\ \mu_{M(y)}(u_y) = \left(\mu_{M(Superior)}\right)^{0.5},\ \mathit{for}\ \ 0 \le \mu_{M(Superior)} \le 1.0 \tag{54}$$

$$y = \mathit{Above\ \ Average},\ \mu_{M(y)}(u_y) = \left(\mu_{M(Average)}\right)^{1.5}\ \ \mathit{for}\ \ 0 \le \mu_{M(Average)} \le 1.0 \tag{55}$$

$$y = \mathit{Below\ \ Average},\ \mu_{M(y)}(u_y) = \left(\mu_{M(Average)}\right)^{0.5}\ \ \mathit{for}\ \ 0 \le \mu_{M(Average)} \le 1.0 \tag{56}$$

$$y = \mathit{Very\ \ Poor},\ \mu_{M(y)}\left(u_y\right) = \left[\mu_{M(Poor)}\right]^2\ ,\mathit{for}\ \ 0 \le \mu_{M(Poor)} \le 1.0 \tag{57}$$

Since there is no standard method of generating membership functions, other similar membership functions for composite linguistic values may be defined and applied to derive or create new linguistic values like those shown in Tables 7-3 and 7-4.

Table 7-3 Compatibility (Membership) Functions of Composite Linguistic Values of X= Importance

Linguistic value, x	**Selected Values of u_x**										
	0.0	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**1.0**
Indeed critical	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.05	0.92	1.0
More or less critical	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.22	0.39	0.89	1.0
Very important	0.0	0.01	0.06	0.56	0.81	1.0	0.81	0.56	0.06	0.01	0.0
More or less important	0.0	0.32	0.50	0.87	0.95	1.0	0.95	0.87	0.50	0.32	0.0
Not Important	1.0	0.90	0.75	0.25	0.10	0.0	0.10	0.25	0.75	0.90	1.0

Table 7-4 Compatibility (Membership) Functions of Composite Linguistic Values of Y = Capability

Linguistic value, y	**Selected Values of u_y**										
	0.0	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**1.0**
Indeed Superior	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.18	0.98	1.0
More or less superior	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.32	0.55	0.95	1.0
Above average	0.0	0.01	0.03	0.21	0.72	1.0	0.72	0.21	0.03	0.01	0.0
Below average	0.0	0.22	0.32	0.59	0.89	1.0	0.89	0.59	0.32	0.22	0.0
Very Poor	1.0	0.64	0.16	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0

It is assumed that the defined membership functions of the linguistic values above represent on how the product development team rates the importance of a requirement and capability of an alternative, and further reflect the meanings of the fuzzy linguistic values used in the case study. The four tables above are also shown graphically in Appendix F. Moreover, it should be pointed out that the defined membership functions both for X and Y are independent from the heuristic algorithm proposed in this work. Additionally, the membership functions are expressed here in the form of either as vector or matrix of numbers rather than as a single value as shown in the next section.

7.7.2 Relating Two Fuzzy Linguistic Variables

After defining the membership functions of the linguistic values of *X* and *Y* to be used, let's cover briefly the methodology for solving basic fuzzy relation equations as proposed by Sanchez [1976] where he defined the fuzzy sets as mappings from sets into complete Brouwerian lattices. His methodology, which is originally based upon the max-min composition, is adapted in the development of the heuristic algorithm for relating two fuzzy linguistic variables *X* and *Y* below.

Take for instance, if a criterion or requirement is *very important* to company's sustainability plan, and a particular option for improvement exhibits an *above average* capability to achieve that criterion, then the fuzzy relation equation (58), based from the work of Sanchez, holds:

$$\mathrm{r}_{\mathrm{x_i y_{ji}}} = \mathrm{y}_{\mathrm{ji}}^{-1} \Theta \mathrm{x_i} \quad (58)$$

where:

x_i = linguistic value of *Importance* assigned to requirement *i* (e.g. very important);

y_{ji} = linguistic value of *Capability* of alternative *j* to meet the specific requirement *i* (e.g. above average);

y_{ji}^{-1} = transpose of y_{ji};

$r_{x_i y_{ji}}$ = linguistic assessment of the relation between x_i and y_{ji};

For example, $\mathrm{r}_{\mathrm{x_i y_{ji}}} = [\mathit{Above\ Average}]^{-1}\,\Theta\,[\text{Very Important}]$

Θ = composite fuzzy relational operator defined such that the membership function of the composite fuzzy relation of y_{ji}^{-1} and $\mathrm{x_i}$ is:

$$\mu_{M(r_{x_i y_{ji}})}(u_x,u_y) = \wedge\left[\mu_{M(y_{ji}^{-1}\Theta x_i)}(u_x,u_y) = \mu^{-1}_{M(y_{ji})}(u_y) \propto \mu_{M(x_i)}(u_x)\right] \quad (59)$$

where:

$\mu_{M(r_{x_i y_{ji}})}(u_x,u_y)$ = membership function of relation of u_x and u_y in *M* ($r_{x_i y_{ji}}$) (in the form of p X q array of numbers or grades of membership)

$\mu^{-1}_{M(y_{ji})}\left(u_y\right)$ = transpose of the membership function of u_y in M(y_{ji}) (in the form of *p X 1* column vector of numbers or grades of membership)

$\mu_{M(x_i)}\left(u_x\right)$ = membership function of u_x in *M* (x_i) (in the form of *1 X q* row vector of numbers or grades of membership)

$\wedge$ = *Minimum* operator

$\propto$ = relative pseudo-complement operator defined such that the elements, a_{pq}, of the membership function (grades of membership) of the composite fuzzy relation of y^{-1}_{ji} and x_i (*p X q* matrix) are determined as follows:

$$\mu^{-1}_{M(y_{ji})}\left(u_y\right)\propto\mu_{M(x_i)}\left(u_x\right)=\begin{Bmatrix}1, & if\ \ a_p^{\mu^{-1}_{M(y_{ji})}(u_y)}\le a_q^{\mu_{M(x_i)}(u_x)}\\ a_q^{\mu_{M(x_i)}(u_x)} & if\ \ a_p^{\mu^{-1}_{M(y_{ji})}(u_y)}> a_q^{\mu_{M(x_i)}(u_x)}\end{Bmatrix}(60)$$

where:

$a_p^{\mu^{-1}_{M(y_{ji})}(u_y)}$ = *p*th element in the *p X 1* column vector of $\mu^{-1}_{M(y_{ji})}\left(u_y\right)$,

$a_q^{\mu_{M(x_i)}(u_x)}$ = *q*th element in the *1 X q* row vector of $\mu_{M(x_i)}\left(u_x\right)$,

a_{pq} = *pq*th element in the *p* X *q* matrix

p=1,…rth rows; q=1,…cth columns

Moreover, a further useful concept for the development of the heuristic algorithm for this study is the intersection (minimum) of several fuzzy relations $r_{x_iy_{ji}}$ at a given alternative *j*, R*j*. *A*ccording to Kaufmann [1975, pp. 60-62], the membership function for the over-all relation, R$_j$ for each *j* is as follows:

$$\mu_{R_j}(u_x,u_y)=\underset{i=1}{\overset{m}{Min}}\left[\mu_{M(r_{x_iy_{ji}})}\left(u_x,u_y\right)\right]\qquad(61)$$

or alternatively, expressed in terms of the elements of the matrices on the right side of equation (61),

$$\mu_{R_j}(u_x,u_y)=\underset{p,q}{Min}\left\{a_{pq}^{\mu_{M(r_{x_1y_{j1}})}},a_{pq}^{\mu_{M(r_{x_2y_{j2}})}},\cdots,a_{pq}^{\mu_{M(r_{x_my_{jm}})}}\right\}\quad(62)$$

where:

$a_{pq}^{\mu_{M(r_{x_i y_{ji}})}}$ = pqth element in the p X q matrix of $\mu_{M(r_{x_i y_{ji}})}\left(u_x, u_y\right)$

$\mu_{R_j}(u_x, u_y)$ = membership function of the over-all relation, R_j(p X q matrix)

To reiterate, the membership functions considered in this study are either in the form of a vector or matrix of numbers or grades of membership. The element of a matrix represents grade of membership.

7.7.3 Heuristic Algorithm

To facilitate the determination of the over-all linguistic value of the *Capability* of an alternative, y_j or eventually the ranking of the options for sustainable system improvement based on relative Hamming distance, a heuristic algorithm (procedure for finding one or more satisfactory solutions to a specific problem) was developed and offered here. See also Figure 7-5 for the flowchart of the proposed heuristic algorithm. This is based on the use of fuzzy linguistic variables defined above to characterise the capability of available sustainable proposals for improvement to satisfy a common set of environmental, quality and economic requirements of strategic interest to an organisation, and to select the "best" option from those available in the implementation of the firm's sustainability plan. A step-wise calculation on how to go about the heuristic algorithm in connection with the case study of this work is shown in section 8.9. Additionally, a numerical example on the calculations involved is shown in the next section.

Procedural Steps:

1. Linguistic descriptions or linguistic values of *IMPORTANCE* (e.g. *indeed critical*) of each of the selected critical environmental, quality and economic requirements as well as linguistic values of *CAPABILITY* (e.g. *superior*) of each of the options for improvement to satisfy each requirement must be established. These descriptions become the linguistic values of the fuzzy linguistic variables *Importance* and *Capability*, x_i and y_{ji}, respectively. These qualitative data should be provided by the product development team or the decision maker.

2. Using the defined membership functions from Tables 7-1 to 7-4, for each combination of the importance (x_i) of m (environmental or quality or economic) requirements and the capability (y_{ji}) of n options for improvement, solve for the membership functions (in the

form of *p X q* array of numbers) of $r_{x_i y_{ji}}$ relations using equation (63). The membership functions for the fuzzy linguistic values of x_i (in the form of *1 X q* vector of numbers) and transpose of y_{ji} (in the form of *p X 1* vector of numbers) are given.

$$\mu_{M(r_{x_i y_{ji}})}(u_x,u_y)=\begin{Bmatrix} 1, & if\ a_{px1}^{\mu^{-1}_{M(y_{ji})}(u_y)} \le a_{1xq}^{\mu_{M(x_i)}(u_x)} \\ a_{1xq}^{\mu_{M(x_i)}(u_x)} & if\ a_{px1}^{\mu^{-1}_{M(y_{ji})}(u_y)} > a_{1xq}^{\mu_{M(x_i)}(u_x)} \end{Bmatrix} \quad (63)$$

3. For each of the options (*j =1,…n*) for improvement, get the minimum among the elements of *m* binary fuzzy relations, $r_{x_i y_{ji}}$, over the common set of *m* criteria using equation (61) or equation (62). Here, the membership functions of over-all relations, R_j, (in the form of *p X q* array of numbers) are determined for each alternative.

4. Set an 'ideal' value of *X*, denoted *x**, which represents the *IMPORTANCE* of implementing the overall sustainability strategy to the future of the company, e.g., *x* =Indeed Critical*. From Table 7-3, the membership function of u_x in the linguistic value of Importance, *Indeed Critical*, is shown in equation (64).

$$\mu_{M(IndeedCritical)}(u_x)=\begin{bmatrix}0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.01 & 0.05 & 0.92 & 1.0\end{bmatrix} \quad (64)$$

5. Determine the over-all membership function of Capability, y_j, for each *j* using the membership function of *x** from step 4 and the membership function of R_j from step 3

using the fuzzy relation equation (65) below

$$y_j^{-1} = R_j \Theta x^{*-1} \quad (65)$$

The membership function of y_j^{-1} (in the form of a *p X 1* vector of numbers) is determined by

$$\mu^{-1}_{M(y_j)}(u_y)=Min\left[\mu_{R_j}(u_x,u_y)\propto\mu^{-1}_{M(x^*)}(u_x)\right] \quad (66)$$

or alternatively, in terms of the elements of matrix in equation (66),

$$\mu^{-1}_{M(y_j)}\left(u_y\right) = \underset{q}{Min}\left\{\begin{bmatrix} 1, & if \;\; a_{pq}^{\mu_{R_j}(u_x,u_y)} \le a_p^{\mu^{-1}_{M(x^*)}(u_x)} \\ a_p^{\mu^{-1}_{M(x^*)}(u_x)}, & if \;\; a_{pq}^{\mu_{R_j}(u_x,u_y)} > a_p^{\mu^{-1}_{M(x^*)}(u_x)} \end{bmatrix}\right\} \quad (67)$$

By getting the minimum for each row of the *p X q* matrix in equation (67), this step eventually yields the membership function (in the form of *1 X q* vector of numbers or grades of membership) for the overall *CAPABILITY* of each of the *j =1,2,..., n* options for improvement, over all *m* criteria, to implement the sustainability strategy of the organisation. The analyst may wish to stop at this point and attempt to assign linguistic values corresponding to the membership functions that result from the computations using Tables 7-2 and 7-4, and select the one (s) that are at least "more or less superior". However, if the membership functions of y_j cannot be converted into linguistic values, proceed to the next step.

6. Assume that the satisfaction of all criteria or requirements at the highest level possible by any option for improvement selected is the most desirable outcome of the decision process. Hence, it is useful to compare each of the membership functions calculated in step 5 with that corresponding membership function of *Capability* of an ideal alternative, let's say *y* = Indeed Superior*. Munda [1995, p.82] posited that to be as close as possible to the perceived ideal is the rationale of human choice and further claimed that humans compare each alternative with the ideal rather than among themselves.

   This step is done by computing the relative Hamming distance, δ_j, (briefly explained in section 6.6) of each of the *n* fuzzy membership functions in step 5 from the 'ideal' [Kaufmann, 1975]:

$$\delta_j = \frac{1}{ne}\sum_{u_y=0.0}^{1.0}\left|\mu_{M(y_j)}(u_y) - \mu_{M(y^*)}(u_y)\right| \quad for \;\; j = 1,2,\ldots,n \quad (68)$$

or alternatively, in terms of the elements of the vectors in equation (68),

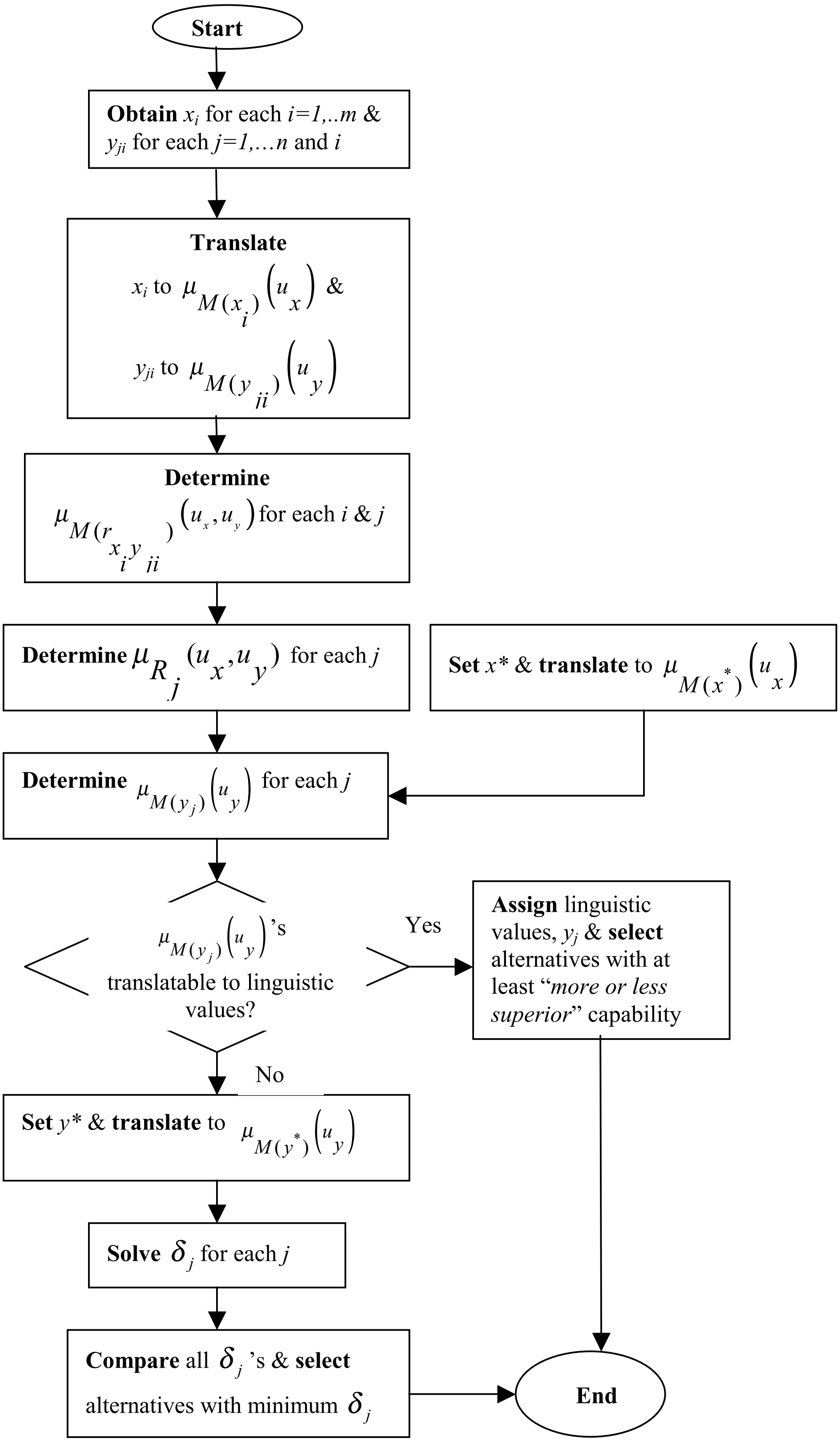
$$\delta_j = \frac{1}{ne}\sum_{q=1}^{11}\left|a_q^{\mu_{M(y)}(u_y)} - a_q^{\mu_{M(y^*)}(u_y)}\right| \qquad (69)$$

where:

ne = number of selected numerical elements (u_y),which is 11 for the present study;

$\mu_{M(y)}(u_y)$ = grade of membership of u_y in *M* (y_j) with respect to option for improvement *j* from step 5 (*1 X q* row vector) ;

Figure 7-5 Flowchart of the Proposed Heuristic Algorithm



$\mu_{M(y^*)}(u_y)$= grade of membership of u_y in *M (y*)* (*1 X q* row vector)

$a_q^{\mu_{M(y)}(u_y)}$ = *q*th element in *1 X q* row vector (membership function) of *M (y_j)* from step 5;

$a_q^{\mu_{M(y^*)}(u_y)}$ = corresponding *q*th element in *1 X q* row vector (membership function) of *M (y*)* (from Table 7-2)

7. Select the optimal (best or satisficing) sustainable option (s) for system improvement as the one (s) which has/have the minimum relative Hamming distance. The relative Hamming distance is used here to determine the distance of each element of the membership function of the calculated capability relative to its corresponding element of the membership function of the assumed ideal capability. It serves here to represent the over-all sustainable performance measure of the proposed options for improvement.

The procedure proposed above is converted into an Excel-based computer model to determine the over-all capability of the alternative linguistically and/or to automate the calculation of relative Hamming distance for all the options. The built-in functions in Excel such as **MIN** (minimum), **IF**..**THEN** (conditional statement), and **ABS** (absolute value) were used to ease the programming effort.

7.7.4 Numerical Example

Step 1:

Assume there are 3 requirements and 1 alternative to be considered and the importance of requirements and the capabilities of alternative to meet each requirement are given as follows:

x_1 *= Critical;* x_2*= Critical;* x_3 *= Very Important*

y_{11}*= Superior;* y_{12}*=Indeed Superior;* y_{13}*=Superior*

The membership functions of the linguistic values are assumed as follows:

$$\mu_{M(Critical)}(u_x) = [0.15 \quad 0.80 \quad 1.0]$$

$$\mu_{M(Very\,\mathrm{Im}\,por\tan t)}(u_x) = [0.06 \quad 0.56 \quad 0.81]$$

$$\mu_{M(IndeedCritical)}(u_x) = [0.05 \quad 0.92 \quad 1.0]$$

$$\mu_{M(Superior)}(u_y) = [0.30 \quad 0.90 \quad 1.0]$$

$$\mu_{M(IndeedSuperior)}(u_y) = [0.18 \quad 0.98 \quad 1.0]$$

Step 2: Solve $\mu_{M(r_{x_i y_{ji}})}\left(u_x,u_y\right)$

According to equation (60 or 63),

$$\mu_{M(r_{x_1 y_{11}})}(u_x,u_y)=\begin{bmatrix}0.30\\0.90\\1.00\end{bmatrix}\propto\begin{bmatrix}0.15 & 0.80 & 1.00\end{bmatrix}$$

$$\mu_{M(r_{x_1 y_{11}})}(u_x,u_y)=\begin{pmatrix}0.30>0.15 & 0.30<0.80 & 0.30<1.00\\0.90>0.15 & 0.90>0.80 & 0.90<1.00\\1.00>0.15 & 1.00>0.80 & 1.00=1.00\end{pmatrix}$$

$$\mu_{M(r_{x_1 y_{11}})}(u_x,u_y)=\begin{pmatrix}0.15 & 1.00 & 1.00\\0.15 & 0.80 & 1.00\\0.15 & 0.80 & 1.00\end{pmatrix}$$

Similarly, one obtains

$$\mu_{M(r_{x_2 y_{12}})}(u_x,u_y)=\begin{pmatrix}0.15 & 1.00 & 1.00\\0.15 & 0.80 & 1.00\\0.15 & 0.80 & 1.00\end{pmatrix}$$

$$\mu_{M(r_{x_3 y_{13}})}(u_x,u_y)=\begin{pmatrix}0.06 & 1.00 & 1.00\\0.06 & 0.56 & 0.81\\0.06 & 0.56 & 0.81\end{pmatrix}$$

Step 3:

According to equation (61 or 62), by getting the minimum among the elements across the 3 matrices, the membership function of R_j

$$\mu_{M(R_1)}(u_x,u_y)=Min\left\{\left[\begin{pmatrix}0.15 & 1.00 & 1.00\\0.15 & 0.80 & 1.00\\0.15 & 0.80 & 1.00\end{pmatrix},\begin{pmatrix}0.15 & 1.00 & 1.00\\0.15 & 0.80 & 1.00\\0.15 & 0.80 & 1.00\end{pmatrix},\begin{pmatrix}0.06 & 1.00 & 1.00\\0.06 & 0.56 & 0.81\\0.06 & 0.56 & 0.81\end{pmatrix}\right]\right\}$$

$$\mu_{M(R_1)}(u_x,u_y)=\begin{pmatrix}0.06 & 1.00 & 1.00\\0.06 & 0.56 & 0.81\\0.06 & 0.56 & 0.81\end{pmatrix}$$

Step 4: Set *x** as *Indeed Critical* and its assumed membership function is as follows:

$$\mu_{M(x^*)}(u_x) = \begin{bmatrix} 0.05 & 0.92 & 1.00 \end{bmatrix}$$

Step 5: Knowing the membership functions of *x** and R_1, according to equation (65 or 66), solve for the membership function of y1

$$\mu_{R_1}(u_x,u_y) \propto \mu^{-1}_{M(x^*)}(u_x) = \begin{pmatrix} 0.06 & 1.00 & 1.00 \\ 0.06 & 0.56 & 0.81 \\ 0.06 & 0.56 & 0.81 \end{pmatrix} \propto \begin{bmatrix} 0.05 \\ 0.92 \\ 1.00 \end{bmatrix}$$

$$\mu_{R_1}(u_x,u_y) \propto \mu^{-1}_{M(x^*)}(u_x) = \begin{pmatrix} 0.06 > 0.05 & 1.00 > 0.92 & 1.00 = 1.00 \\ 0.06 > 0.05 & 0.56 < 0.92 & 0.81 < 1.00 \\ 0.06 > 0.05 & 0.56 < 0.92 & 0.81 < 1.00 \end{pmatrix}$$

$$\mu_{R_1}(u_x,u_y) \propto \mu^{-1}_{M(x^*)}(u_x) = \begin{pmatrix} 0.05 & 0.92 & 1.00 \\ 0.05 & 1.00 & 1.00 \\ 0.05 & 1.00 & 1.00 \end{pmatrix}$$

By getting the minimums (**Min**) for each row across columns of the preceding matrix,

$$\mu^{-1}_{M(y_1)}(u_y) = \overset{3}{\underset{q=1}{Min}} \left\{ \mu_{R_1}(u_x,u_y) \propto \mu^{-1}_{M(x^*)}(u_x) \right\}$$

$$\mu^{-1}_{M(y_1)}(u_y) = \overset{3}{\underset{q=1}{Min}} \begin{pmatrix} 0.05 & 0.92 & 1.00 \\ 0.05 & 1.00 & 1.00 \\ 0.05 & 1.00 & 1.00 \end{pmatrix}$$

$$\mu^{-1}_{M(y_1)}(u_y) = \begin{bmatrix} 0.05 \\ 0.05 \\ 0.05 \end{bmatrix}$$

$$\mu_{M(y_1)}(u_y) = \begin{bmatrix} 0.05 & 0.05 & 0.05 \end{bmatrix}$$

Step 6: Set *y** as *Indeed Superior* and its assumed membership function is as follows:

$$\mu_{M(y^*)}(u_y) = \begin{bmatrix} 0.18 & 0.98 & 1.0 \end{bmatrix}$$

The relative Hamming distance of Alternative 1 is:

$$\delta_1 = \frac{1}{3}\left[|0.05 - 0.18| + |0.05 - 0.98| + |0.05 - 1.0| \right]$$

$$\delta_1 = 0.67$$

Step 7: Repeat the above procedure for other alternatives and choose the lowest δ_j.

7.8 Sensitivity and Statistical Analyses

Sensitivity analyses are conducted to answer "what-if" scenarios and in effect to observe how the ranking results change as there are changes in data inputs. Additionally, a statistical analysis, specifically the analysis of variance (ANOVA), is conducted to check the null hypothesis that the ranks of the considered options for improvement, which are based on the expected means of relative Hamming distance of the options for improvement, are the same. Many people who are working in the field of product development advised that the more time spent in productively evaluating competing concepts, the shorter will be the total design time and the better the product will be at the end. These two types of analyses aid to confirm the selected option/s among the considered alternatives.

By definition, ANOVA is used to test the differences of at least 2 means (Anderson, Sweeney & Williams, 2000, p. 392; Kazmier, 1976, p. 218). A basic assumption underlying the analysis of variance is that the several sample means were obtained from normally distributed populations having the same variance σ^2. However, the test procedure has been found to be relatively unaffected by violations of the normality assumption when the populations are unimodal and the sample sizes are approximately equal [Wonnacott & Wonnacott, 1990, p. 329].

Assuming that ANOVA test is applicable in the present work, the null hypothesis and alternative hypothesis are characterized as follows:

$$H_0 : \bar{\delta}_1 = \bar{\delta}_2 = \bar{\delta}_3 \cdots \bar{\delta}_n \quad (70)$$

$$H_1 : \bar{\delta}_1 \neq \bar{\delta}_2 \neq \bar{\delta}_3 \cdots \bar{\delta}_n \quad (71)$$

H₀ denotes null hypothesis that the expected means $(\bar{\delta}_j, j = 1,2,...n)$ of relative hamming distance among the alternatives are the same. H_1 signifies the alternative hypothesis that the expected means of relative Hamming distance among the options for improvement are not equal or different from each other. The decision to accept or reject the null hypothesis depends on the computed or observed Fisher (*F*) ratio in equation (72) as compared to the critical *F*-value.

$$F = \frac{n s_{\bar{x}}^2}{s_p^2} \quad (72)$$

where:

$s_{\bar{x}}^2$ = variance in expected means of relative Hamming distance

s_p^2 = pooled variance

n = number of runs made for each alternative

The critical values of the F distribution when the H_o is true can be obtained from tables of F critical points, which are usually provided in appendix of any statistics book. When the calculated F-value is lower than or equal to critical F-value, then the null hyphothesis is acceptable. Otherwise, the null hypothesis is rejected and the alternative hypothesis is accepted. Hence, the larger is F, the less credible is the null hypothesis that the ranks of the options for improvement are similar. Alternatively, one can measure the credibility of H_0 by finding its p-value (probability in the tail of the F distribution beyond the observed value). The larger the F-ratio, the smaller is the p-value and consequently the stronger is the grounds for rejecting the H_0.

In the next section, the methodology developed in this chapter is applied for the selection of optimal sustainable option for improvement of light fitting system.

8 Application of the Developed Methodology

The developed conceptual approach which was discussed in the preceding chapter is applied here for evaluating the suggested options for improvement of a light fitting system and selecting the best alternative in conjunction with the company's plan to maintain its competitive advantage and at the same time meeting the current concern for sustainability.

8.1 Brief Company Background and Description of the Reference Product System

A case project on the improvement of light fitting system has been conducted in cooperation with Lumilight Electric Product and Lighting Incorporated, one of the manufacturers of light fittings in the Philippines. This Philippine company has been in the industry since 1965. Recently, the company has undertaken a product development project of light fitting system. At present the said company works to improve their environmental performance in three different areas. These are energy conservation, raw material reduction in new products, and recycling. In addition the manufacturing firm through its product development department aims to collaborate closely with customers when developing new products and makes special efforts to improve continuously its product quality by developing more efficient manufacturing processes, materials administration, production planning and organisation.

Essentially, environmental care is an important part of the Lumilight's production and economic activities. The four basic principles of its operation are [Lumilight, 1999]:

- sustainable development:
- consideration of environmental issues at the source;
- environmental effects assessment; and
- co-operation with the authorities.

These basic principles mentioned above are the basis of its environmental policy statement as defined below:

1. Environmental aspects shall be considered at every stage of the organization in the planning of operation, decision-making processes and implementation activities.
2. Continuous development of production methods and products so that their harmful effects are minimized with respect to nature, health, resources and aesthetic values.

3. In-house production will favour environmental friendly methods and materials and activities will be geared to promote recycling of raw materials and products.
4. The minimum requirement is compliance with all applicable environmental laws, regulations and authorities' orders.
5. Continuous improvement in environmental issues through personnel training and guidance.
6. Striving to ensure that their subcontractors comply with environmental laws and orders.
7. Responsibility for environmental care is divided to all levels of the line organization in the same way as for any other activity.
8. Successful environmental care is based on positive and responsible attitude of the whole personnel.

Moreover, the reference product for this case study is a light fitting system, 2 X 10 W splash proof universal, for office applications. This product system is 70 cm long and 24 cm wide with a traditional reactor. The weight of the fitting is about 3.5 kg, which is mainly composed of aluzinc (alloy of 58% by weight Aluminium and 42% by weight Zinc), steel, acrylic and acrylonitrile butadiene styrene (ABS) plastic materials, reactor and aluminium reflector. The general market share of this product in the Philippines is 60.3 percent. Figure 8-1 shows the reference flow and product components of the light fitting system. Figure 8-2 displays the life cycle product and process structure of the light fitting system.

The data that were used in this case study was primarily provided by the said company. However, other relevant information was taken from different sources, which might be of unknown reliability and accuracy.

8.2 Abridged Life Cycle Assessment of Light Fitting System

The goal of streamlined LCA in this case study is to inventory and assess the environmental emissions and consumptions of a reference light fitting system and then to use these results as a basis to determine potential product system improvements at an early stage. This assessment eventually aids in assisting the selection of best alternative among the different concepts for product system improvement with regards to environmental consideration. The life cycle stages considered in the case study are from raw material acquisition to raw material processing, product assembly, use and then waste management.

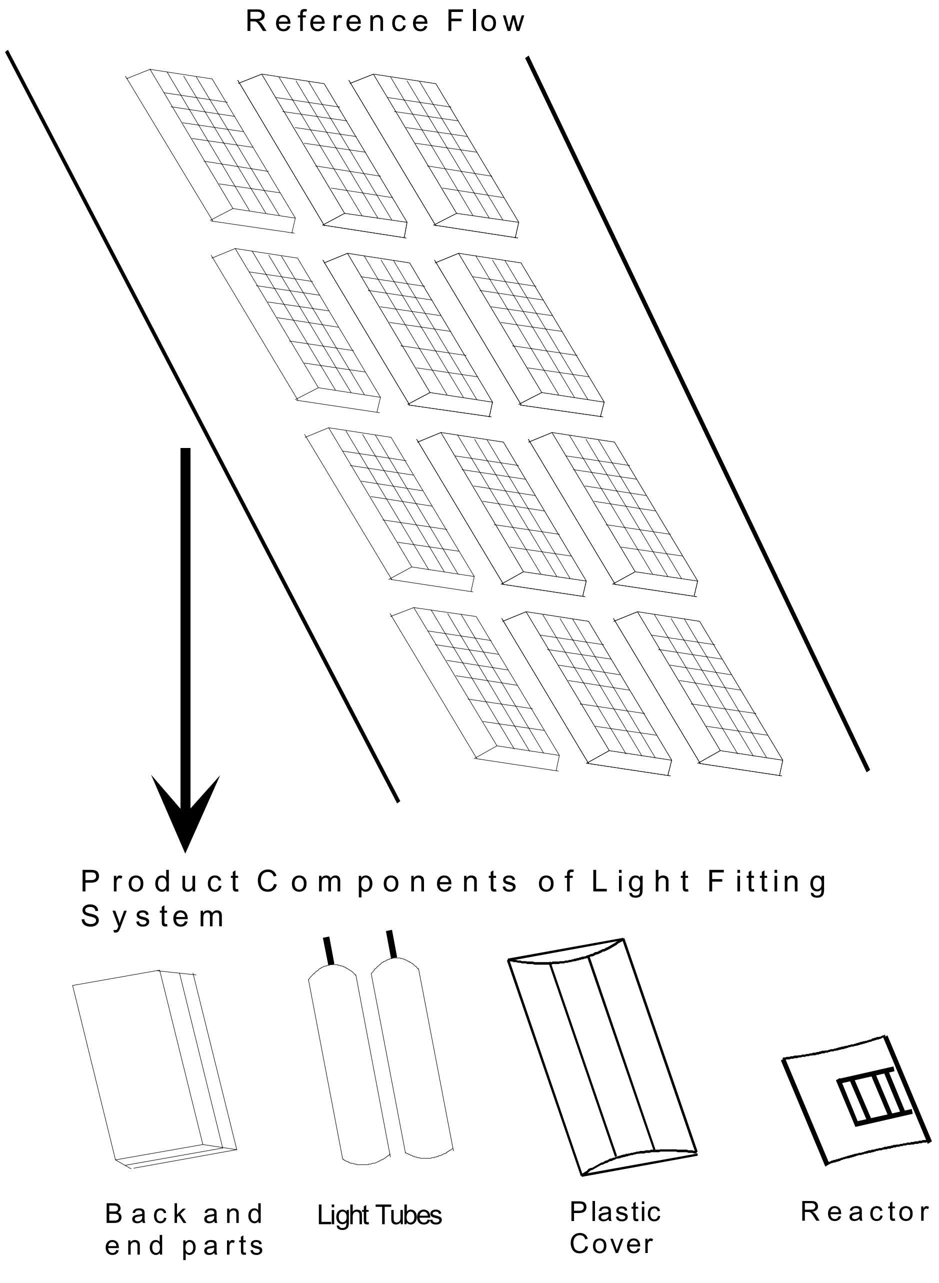


Figure 8-1 Reference Flow and Product Components of Light Fitting System

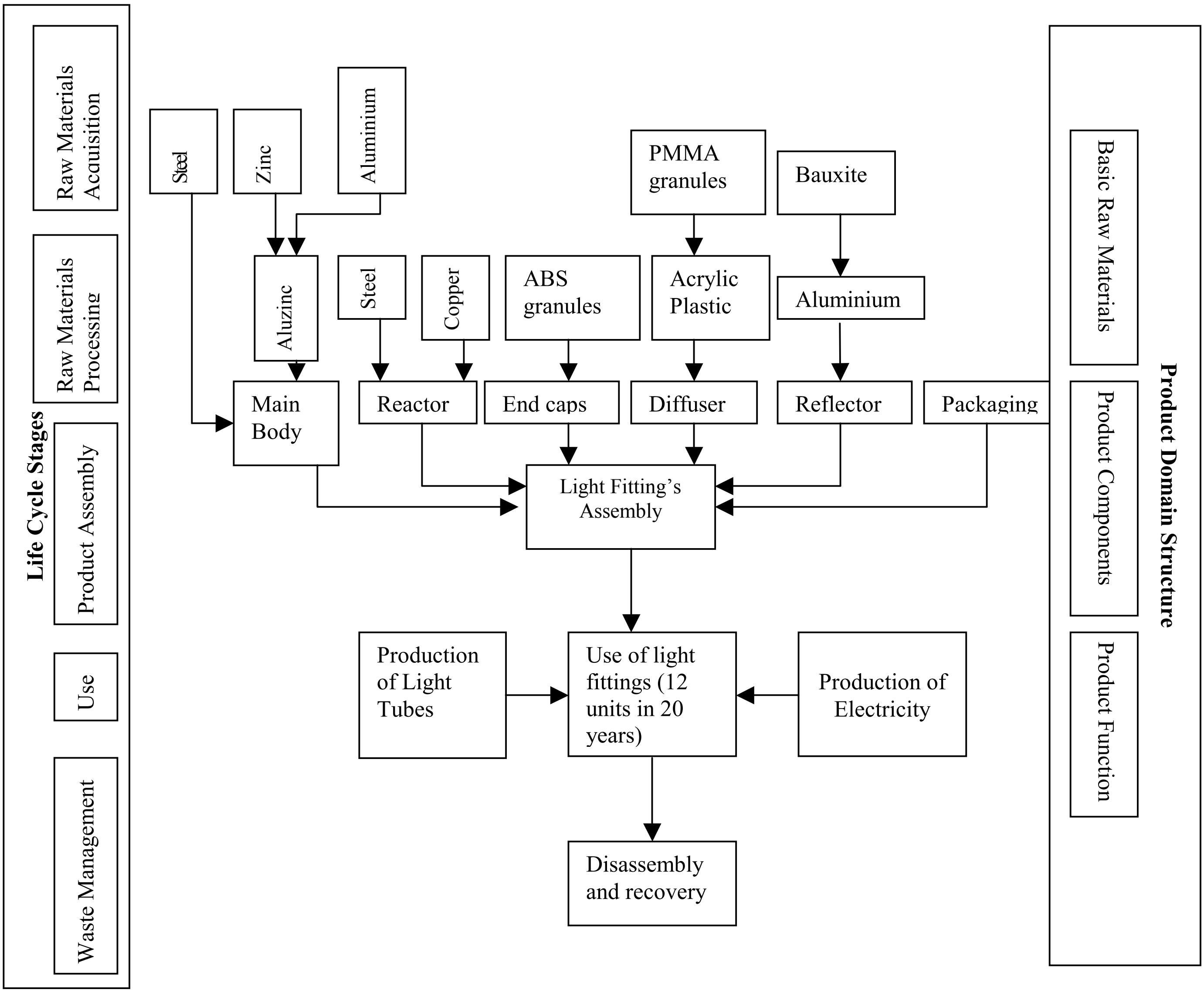


Figure 8-2 Life Cycle Product Structure and Process Flow Diagram of Light Fitting System

8.2.1 Definition of Functional Unit, System Boundaries and Conditions

For the LCA part of the present study, the following functional unit, system boundaries, and simplifying conditions formed the basis of the life cycle assessment of the reference light fitting system:

- The functional unit is defined to be an office area of 25 m^2 in order to establish what kind of light fitting system to use, and also to compare the different product system improvement alternatives. To fulfil the minimum requirements for electric light in a 25-

m^2-office area (given a lighting intensity of 450 lux), 12 light fittings of 2 x 10 W are assumed to be needed.

- The life span of the light fittings is assumed to be 20 years.
- Raw materials and components that are making up less than 5% of the light fittings are neglected.
- Data on steel and packaging (corrugated paper board) for light fittings were obtained from LCA inventory Tool (LCAiT) database. The data includes discharges and energy consumption from the production of 1 kg of raw material.
- 100% raw steel was assumed to be used in the production of main part and reactor components of light fitting system. Data derived from the LCAiT database was used.
- Data from Boustead and Hancock [1979] was used for the energy consumption of the ABS-granules production. ABS granules are produced from the reaction of acrylonitrile, polybutadiene, and styrene. Energy consumptions during the transport of raw materials are excluded.
- The data on styrene and polybutadiene is derived from Tables 15, 16, 18, and 19 in Plastic Waste Management Institute (PWMI) 's Eco-profiles of the European Plastics Industry, Report 5: Polystyrene [Boustead, 1993a]. These tables describe total energy consumption (direct and indirect) and total discharges per kg of product from crude oil extraction to finished product. It is assumed that this is a representative data for polybutadiene and styrene.
- Acrylonitrile (=propenenitrile) is usually produced through catalytic gas-phase oxidation of propene into acrolein (C_3H_4O), followed by conversion into acrylonitrile. The emission profile for propene is derived from Tables 3 and 6 in PWMI's' Eco-profiles of the European Plastics Industry, Report 3: Polyethylene and Polypropylene [Boustead, 1993b]. For the conversion of propene into acrylonitrile, 20% larger energy consumption and an equally large discharge increase are assumed. The emission profile on fuel oil is used.
- The acrylic diffuser is made of polymethyl methacrylate (PMMA), which is produced from alkene (C_5H_9) via oxidation into ester ($C_5H_8O_2$) and followed by polymerisation into PMMA. The same discharge profile as for polypropylene, as shown in Tables 24 and 26 in PWMI's Report 3, is assumed.
- Data on aluminium that were taken from Packaging and Environment [Tillman et al., 1992] is used. The data includes anode production, electrolysis and casting.

- Discharges and energy consumptions related to the production process at Lumilight Inc. are allotted among the raw materials (components) based on the products' mass distribution.
- It is assumed that the expected lighting time per year of the light fitting system is 3000 hours.
- It is assumed that there are 20 replacements for light tubes and igniters.
- The discharges and energy consumptions are calculated in relation to a 20-year life span of the reactor (efficiency loss of 7 W). This results in a power consumption of 43 watts for each light fitting system.

8.2.2 Inventory of Material-, Energy- and Waste Flows

The inventory of mass and energy inputs and outputs, which was partly provided from the above-mentioned company, is an important aspect of doing a life cycle assessment. Missing information was taken from different literature and databases, which are not necessarily of high quality and reliability. The gathered limited data is then analysed and classified into appropriate environmental impact categories as shown below. The summary of the life cycle inventory data obtained is shown in Appendix E.

8.3 Environmental Profile Analyses of the Reference Light Fitting System

To quickly see and focus the efforts on the major environmental emissions and at which stage these emissions occur, environmental profiles were drawn for each environmental emission across the product life cycle stages. These profiles are shown in the next succeeding sections. As shown from these profiles, the main environmental problems related to the light fitting system are global warming due to carbon dioxide (CO_2), acidification due to sulphur dioxide (SO_2) and nitrogen oxides (NO_x), toxic effects from polyaromatic hydrocarbons (PAHs), human toxicity and ecotoxicity of air due to SO_2 and NO_x , and consumption of fossil fuels. Global warming, acidification, and consumption of fossils were found to be mostly associated with the use of light fittings, rather than on its production. PAH's problem, on the other hand, is mainly due to emissions from the production of the aluminium reflector and the manufacture of aluzinc (alloy of aluminium and zinc) component for the light fitting system. With respect to individual components of the light fitting system, the manufacture of aluminium reflector, reactor and aluzinc-main body contributed predominantly to environmental impacts.

In this case study, the environmental performance metrics considered include weights of product components, total energy consumption during the product life cycle, generated air emissions during production and greenhouse gases released over life cycle.

8.3.1 Components' Weights of Light Fitting System

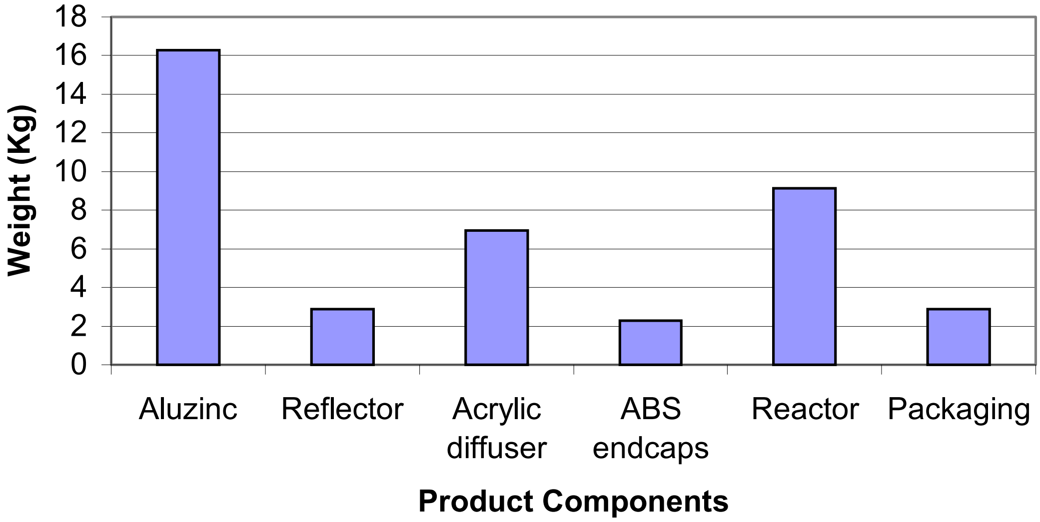


Figure 8-3 Weights of Light Fitting Systems' Components

Figure 8-3 shows the various product system components' share by weight in relation to the functional unit of 12 light fitting systems (see also Appendix E for the tabulated data). The weight of the component reflects the amount of materials used for the manufacture of the whole product system. The above figure indicates that the top two parts of the light fitting systems that weigh the most are the aluzinc-made main body and the reactor, which both chiefly contain steel, a total of 23.994 kg. The third important component is the acrylic diffuser, which made up about 7 kg of Polymethyl Methacrylate (PMMA) granules. The aluminium used for reflector, ABS granules for end caps, and cardboard for packaging are weighing less than 3 kilograms each. Hence, to lower the weight of product system, it requires a reduction of the amount of raw steel consumed. Reducing the mass of a product through reducing the amount of materials used for key components is the surest and most direct way of achieving waste reduction [Fiksel, 1996, p.10].

8.3.2 Estimated Energy Consumption of Light Fittings

Energy is another kind of resource that is consumed during the life cycle stages of the light fitting system. Figure 8-4 displays the energy consumption for the production of each component and for the other stages of the life cycle of the product system (see also Appendix E for the tabulated data). It is shown in the figure below that the greatest energy consumption occurs during the consumers' usage of the light fitting systems.

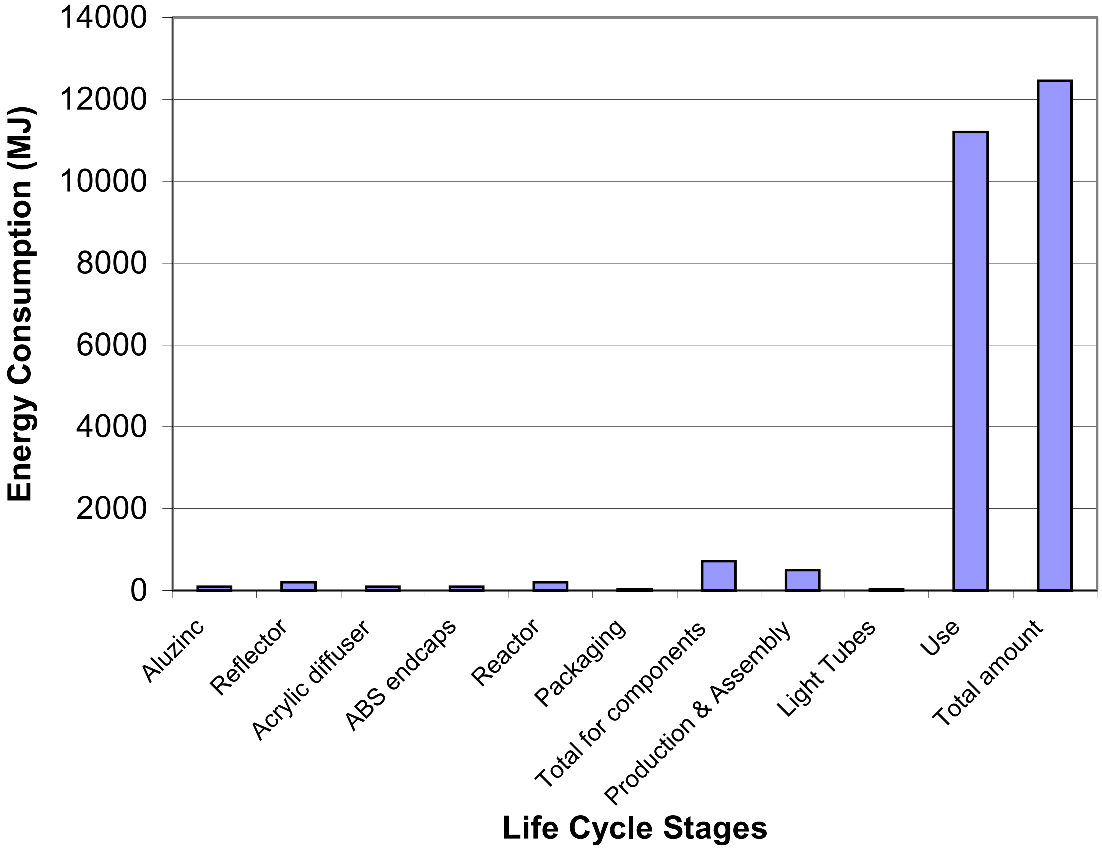


Figure 8-4 Energy Consumption Throughout the Life Cycle of 12 Light Fittings

8.3.3 Global Warming Potential

Global warming is the environmental impact category that takes into consideration the emissions of certain substances such as carbon dioxide that may contribute to an additional atmospheric warming, and thus may lead to a change in climate. Throughout the life cycle stages of light fitting systems, CO_2 emission is found to be the prime contributor to the environmental category - global climate change. Figure 8-5 indicates that the user phase in the life cycle stages contributes the most of CO_2 emissions and it is followed by the production of light tubes. Carbon dioxide is produced from the burning of fossil fuels to generate electricity.

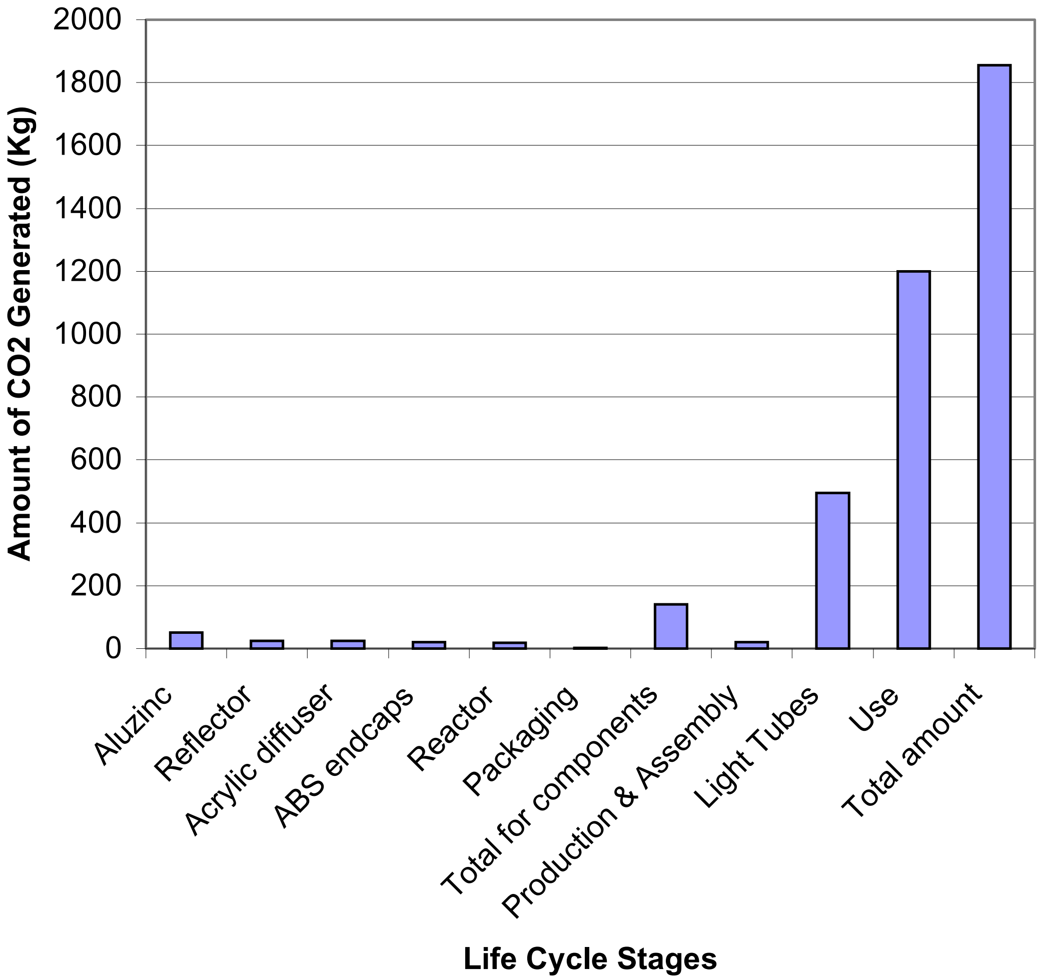


Figure 8-5 Emission of CO_2 Throughout the Life Cycle of 12 Light Fittings

As illustrated in Figure 8-5, the production of components and the assembly of light fittings contribute relatively minimal to the total CO_2 emissions throughout the life cycle, which is only about 4-5%. However, if one considers individually the carbon dioxide emission in the production of the components, the manufacture of aluzinc component contributes the most CO_2 emissions. If one evaluates the ratio of carbon dioxide to weight of material, it is the production of aluminium reflector that contributes substantially to the CO_2 emissions.

8.3.4 Acidification, Humantoxicity and Ecotoxicity of Air

In the light fittings' case, the contribution to acidification, humantoxicity and ecotoxicity of air results from the emissions of SO_2 and NO_x. It is the emission of SO_2 that primarily contributes to these environmental impacts since the total volume of SO_2 emitted are larger the NO_x, and also the effects of SO_2 on acidification, ecotoxicity in air and human toxicity are more severe than the effects of NO_x as indicated by their impact assessment factors [Rentz et al., 1999]. Figure 8-6 to Figure 8-9 illustrate the allocation of these emissions that contributes to these environmental problems.

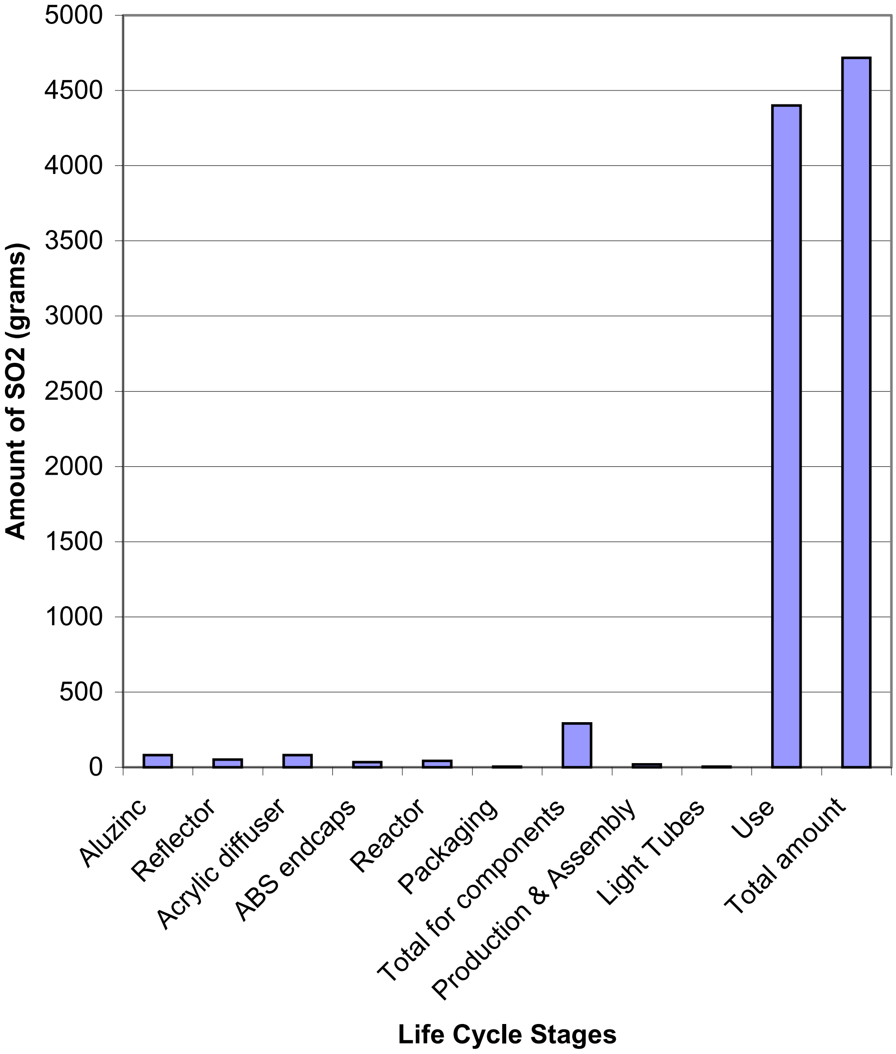


Figure 8-6 Emission of SO_2 Throughout the Life Cycle of 12 Light Fittings

As portrayed in Figure 8-6, it is during the user phase again that the largest SO_2 emissions occur. This is principally due to the burning of fossil fuels (which contains sulphur) when producing energy. The SO_2 emissions during the production of material components are very negligible in comparison with the users' phase. The production of components contributes only about 5% of the total SO_2 pollution throughout the product's life cycle.

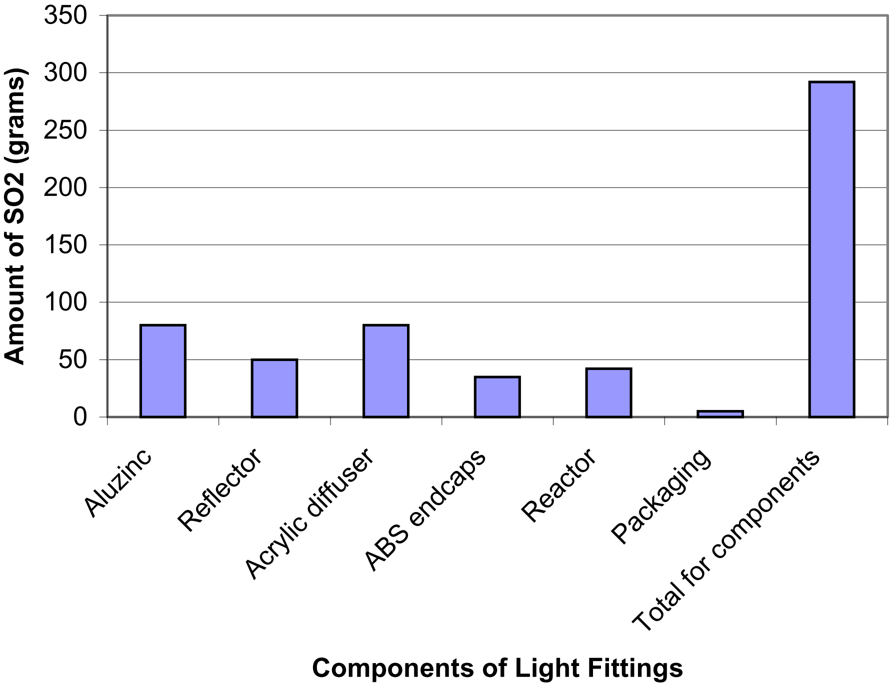


Figure 8-7 Emission of SO_2 from the Production of Components of 12 Light Fittings

In component basis, it is during the production of aluzinc material and the acrylic diffuser that most amounts of SO_2 emissions are generated as shown in Figure 8-7. However, if the ratio of sulphur dioxide to the mass of material used as reference, then it is the production of aluminium reflector that substantially generates SO_2 emissions.

Likewise, as displayed in Figure 8-8, it is during the user phase that the largest NO_x emissions occur. Like SO_2, this is also chiefly due to the burning of fossil fuel in producing electrical energy. As illustrated in Figure 8-9, with respect to the production of individual product components, the manufacture of acrylic diffuser generates the largest amount of NO_x emissions in terms of its total amount and/or per weight basis. The NO_x emissions of the rest of the product system components are below 50 grams. Additionally, NO_x emission could also contribute to the environmental problem of nutrification. The problem of nutrification takes into consideration the damage caused by the excessive input of nutrients into terrestrial and aquatic systems [Geldermann et al., 1999].

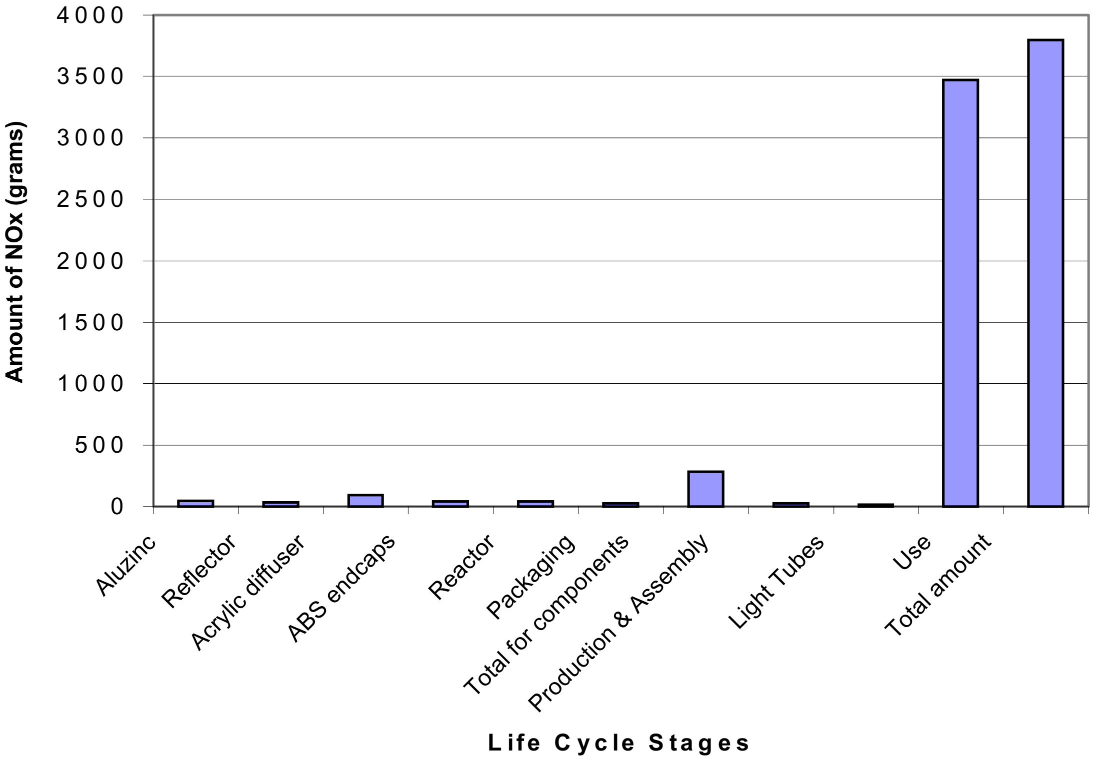


Figure 8-8 Emission of NO_x Throughout the Life Cycle of 12 Light Fittings

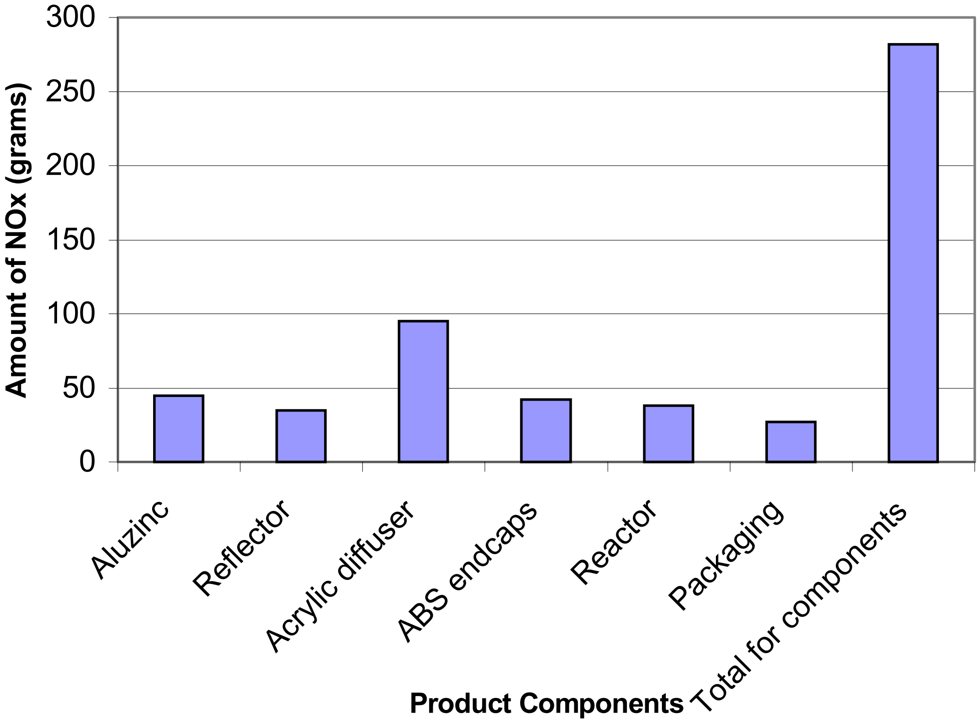


Figure 8-9 Emission of NO_x from the Production of Components for 12 Light Fittings

8.3.5 Photochemical Oxidants Formation and Toxic Effects on the Maritime Environment

Throughout the life cycle of the light fitting system, the emissions of various hydrocarbons (HC), NO_x and CO contribute to the formation of photochemical oxidants, i.e. ground level ozone formation, which damages vegetation and impair human health. Figure 8-10 exhibits the emission of Non Methane Volatile Organic Compounds (NMVOC). Another group of volatile organic compounds (VOC), which has toxic effects on the maritime environment, is the polyaromatic hydrocarbons (PAH) and its environmental profile is presented in Figure 8-11.

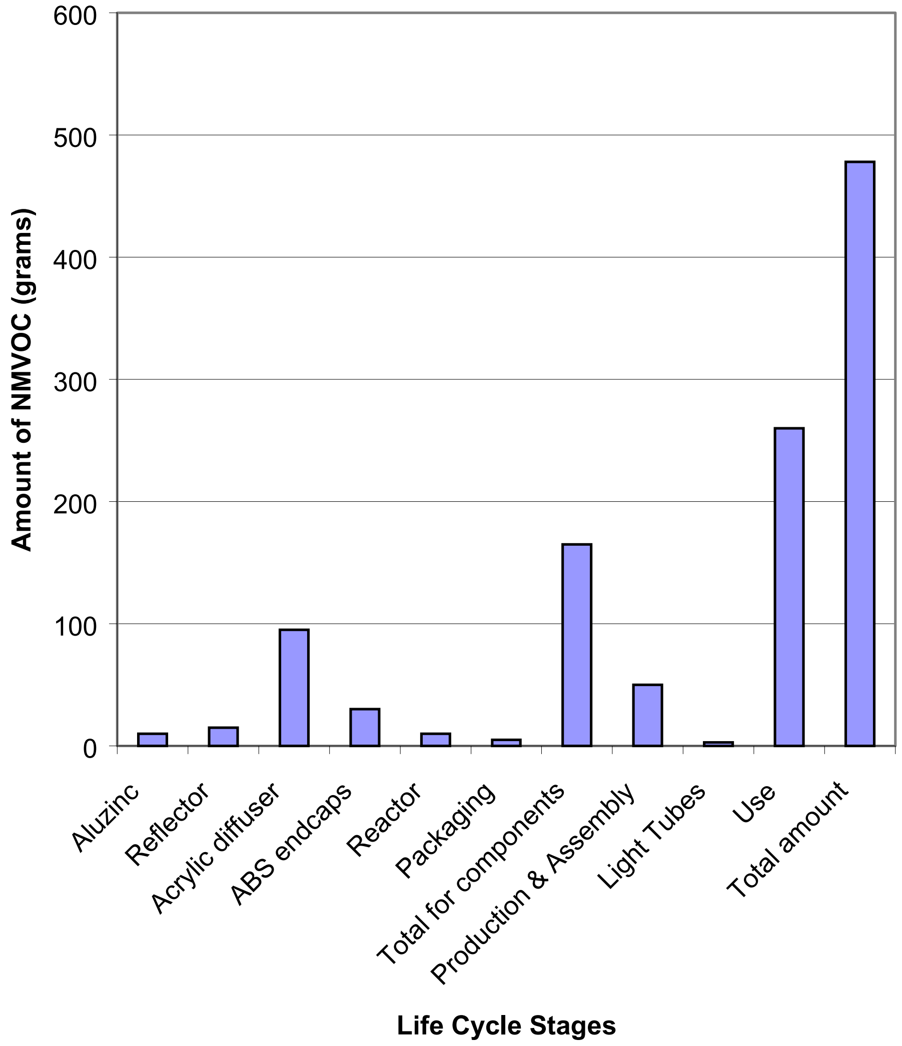


Figure 8-10 Emission of NMVOC Throughout the Life Cycle of 12 Light Fittings

As displayed in Figure 8-10, the largest emission of NMVOC is generated in the user phase of the life cycle. This is a consequence of burning of fossil fuel to produce electricity. This is followed by the manufacture of the product components. The NMVOC emission is due first to the manufacture of acrylic diffusers and then by the production of ABS end-caps, which collectively contributes almost one-third of the total NMVOC emission. The assembly of light fittings at Lumilight Electric Product and Lighting, Inc. generates a notable amount of NMVOC emissions that is about 10% of the total. NMVOC emission contributes the most in comparison to any other emissions reported in this case study. Thus, by reducing the NMVOC emission during the production of components, one could significantly reduce the generated pollution and consequently improve the environmental performance of the production process. This could be one of the significant initiatives for sustainability that the said company can focus on.

In Figure 8-11, the emission of polyaromatic hydrocarbons (PAH) is due largely to the production of two components of the light fitting system. These components are the aluzinc-main body and the reactor. This PAH emission comes from the processing of steel for the aluzinc-main body and reactor components. The other stages of the life cycle do not produce this type of emission.

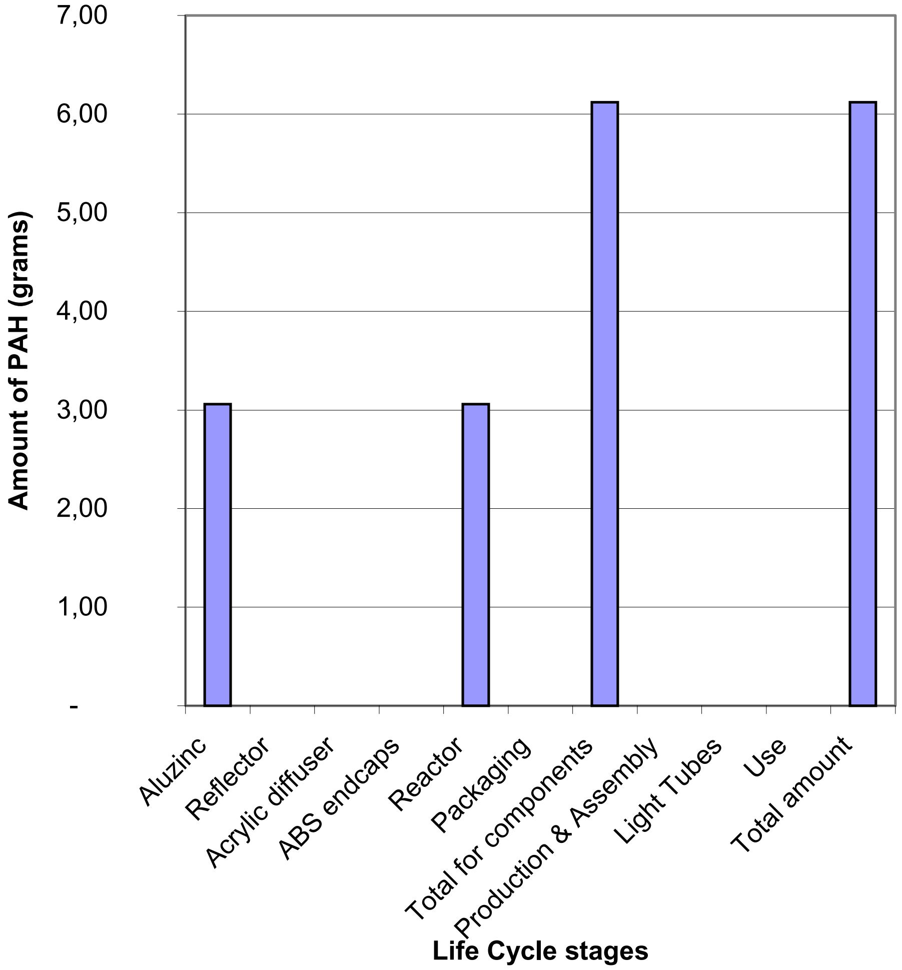


Figure 8-11 Emission of PAH throughout the Life Cycle of 12 Light Fittings

8.4 Green House (Matrix) of the Light Fitting System

Knowing the emissions and at which stage in the life cycle of light fitting system these emissions are created, one can now construct a green matrix or house for the light fitting system. This matrix (house) shows the relationships between the important environmental criteria and the emissions and energy consumptions of the light fittings and also the weights of these environmental criteria such as displayed in Table 8-1 below (see also section 7.2 for explanation and on how the values are obtained or calculated). The data used for the inventory analyses of the proposed alternatives are estimated by analogy with respect to the reference system. The environmental benchmarks are obtained from comparing and getting the minimums among the emission or consumption values for the options considered but alternatively, emission limits for water, air, and land as provided by environmental agencies could also be used if available. The ranking of the emissions and consumptions is based on the calculation of environmental impact potential importance (EIPI) rating. EIPI rating is equal to sum of the product of normalised weight of the environmental requirements and the normalised impact potential factors of emissions with respect to its environmental impact category. The impact potential factor is equal to the product of impact assessment factor (given in Appendix H, an extract from tables in Rentz et al. [1998]) and the ratio of the weight of emission to the total weight of the functional unit considered. For example, the impact assessment factor of CO_2 is 1 kg CO_2-equivalent/kg emitted pollutant, the amount of CO_2 emissions during the life cycle assessment of 42 kilograms of 12 light fitting systems is 1864 kilograms (from Appendix E), then the impact potential factor is **44.38** kilograms of CO_2 equivalent ($= \frac{1864\,kg}{42\,kg} X\ 1\,kg\ CO_2 - equivalent$). The normalised impact potential factor of CO_2 is equal to $\frac{44.38\,kg\ CO_2 - equivalent}{44.38\,kg\ CO_2 - equivalent}$ =**1.0**. Thus, the EIPI rating of CO_2 is equal to $1.0\,kg\ CO_2 - equivalent\ X\ 0.14 =$ ***0.14*** *kg CO2-equivalent*. The impact potential importance rating of the emissions or consumptions to the environment serves as a basis for ranking. The greater the impact potential importance of the emission, the more environmentally critical it is and thus, it should be addressed immediately.

In Table 8-1, the four most significant environmental criteria are reduced global warming potential, reduced acidification potential, reduced humantoxicity and reduced conversion of fossil fuels. As indicated in the last row of Table 8-1, the emissions that have to be focused critically, in the case of light fitting system, are the nitrogen oxides and sulphur dioxide. The higher the impact potential importance rating, the critical is the substance and thus, more effort or resources should be allocated for its reduction to improve the environmental performance of the product or the process. Additionally, in this matrix, the estimated (by analogy) amounts of emissions of the different alternatives for system improvement are reported and compared to the amount of emissions of the reference system to establish environmental benchmarks for emission reduction. Lastly, the triangular portion of the green house is not included in this case study because the data for this aspect is not yet available.

Table 8-1 Green House (Matrix) for the Light Fitting System

	CO_2	**NO_x**	**SO_2**	**NMVOC**	**PAH**	**Fossil Fuels**	**Weight**	**Normalised Weight [i]**
Environmental Criteria								
Reduced [a] global warming potential	**44.38**	**-**	**-**	**-**	**-**	**-**	**5**	**0.14**
Reduced [b] acidification potential	**-**	**0.06**	**0.11**	**-**	**-**	**-**	**5**	**0.14**
Reduced [c] conversion of fossil fuel	**-**	**-**	**-**	**-**	**-**	**1.92**	**5**	**0.14**
Reduced [d] impairment of maritime environment (PAH)	**-**	**-**	**-**	**-**	**7.29**	**-**	**4**	**0.11**
Reduced [e] Photochemical oxidation potential	**-**	**-**	**-**	**4.51**	**-**	**-**	**4**	**0.11**
Reduced [f] Nutrification Potential	**-**	**0.01**	**-**	**-**	**-**	**-**	**4**	**0.11**
Reduced [g] Humantoxicity	**-**	**1.76**	**2.74**	**-**	**-**	**-**	**5**	**0.14**
Reduced [g] Ecotoxicity of Air	**-**	**1.76**	**2.74**	**-**	**-**	**-**	**4**	**0.11**
Reference [h] System	**1864**	**3.7**	**4.6**	**0.46**	**0.0061**	**12350**		
Option 1[h]	**1847**	**3.63**	**4.52**	**0.40**	**0.0056**	**8757**		
Option 2 [h]	**1874**	**3.7**	**5.10**	**0.46**	**0.0059**	**15000**		
Option 3 [h]	**1857**	**3.67**	**4.94**	**0.46**	**0.0038**	**11676**		
Option 4 [h]	**1857**	**3.63**	**4.43**	**0.41**	**0.0038**	**10553**		
Option 5 [h]	**1892**	**3.75**	**4.89**	**0.43**	**0.0060**	**10778**		
Option 6 [h]	**932**	**1.18**	**1.92**	**0.27**	**0.0034**	**12350**		
Benchmarks/ [h] Emission Limits	**932**	**1.18**	**1.92**	**0.27**	**0.0034**	**10553**		
Environment Impact Potential [i] Importance (EIPI) Rating	**0.14**	**0.27**	**0.26**	**0.11**	**0.11**	**0.14**		

Legend: [a] values in kg of CO_2 equivalent; [b] values in kg of SO_2 equivalent; [c] values in kg; [d] value in the row raised to E-05 (kg); [e] value in the row raised to E-03 (kg ethane equivalent); [f] value in kg of PO^{3-}_4 equivalent; [g] values in the row raised to E+06 (m^3 air); [h] values in the row are in kg except for the column of fossil fuels expressed in Mega joules (MJ); [i] is dimensionless; - denotes "not applicable".

8.5 Cost Profile Analysis of Light Fitting System Alternatives

The life cycle costs for the user of light fittings are determined on the basis of the LCA's functional unit of a 25-m^2 room illuminated with 12 light fittings over 20 years. For the case study, the LCC is computed from the sum of cost of energy consumed, cost of light fittings and costs of light tubes. As shown in Figure 8-12, nearly all costs of the reference light fitting system are related to purchasing costs of the 12 light fittings in the first year, which can add up to 90% of the total costs. However, over a 20-year period, energy costs made up the largest share of total costs, followed by the cost of light tubes and then the cost of light fittings. For the reference light fitting system, the cost of light fittings is estimated to be constantly decreasing by a factor of 95.24 % from 2004 to 2019 with respect to the base year (2000). For the cost of tubes, it is estimated that the cost increases to 3.33 times in 2004 to 6.33 times in 2009 to 9.33 times in 2014 to 12 times in 2019 with respect to the base year (2000). For energy consumption, it is reckoned that the cost increases to 5 times in 2004 to 8.5 times in 2009 to 13 times in 2014 and then to 19 times in 2019 with respect to the base year (2000). For example, in year 2004, the estimated cost of reference light fittings is US$ 1002.84 x 0.9524 = US$ 955.08; the estimated cost of light tubes is US$ 143.26 x 3.33 =US$ 477.54; the estimated cost of energy consumed is US$ 95.51 x 5 = US$ 477.54. With respect to the functional unit of 25-m^2 office area, the estimated total life cycle cost of the reference light fitting system is slightly above US$ 4500.00 or about US$ 4536.00. The life cycle cost profiles of the other alternatives, which were estimated by analogy, are presented in Figure 8-13. In this figure, it is estimated that the forecasted LCC for the alternative, which recommends the use of energy conserving equipment, is around 73% and for the alternative that suggests the change to higher wattage armature system is around 69% lower than the reference light fitting system. The forecasted LCCs of the other alternatives are estimated to be similar and do not differ much with respect to the reference system.

Since the life cycle costs of the alternatives were only estimated by analogy, which is usually the case in the preliminary stage of product or system development, these estimated costs are considered imprecise and lacking reliability. The lack of concrete detailed data at the early product development phase, where most of the information are uncertain, prevents us to calculate the life cycle cost with certainty.

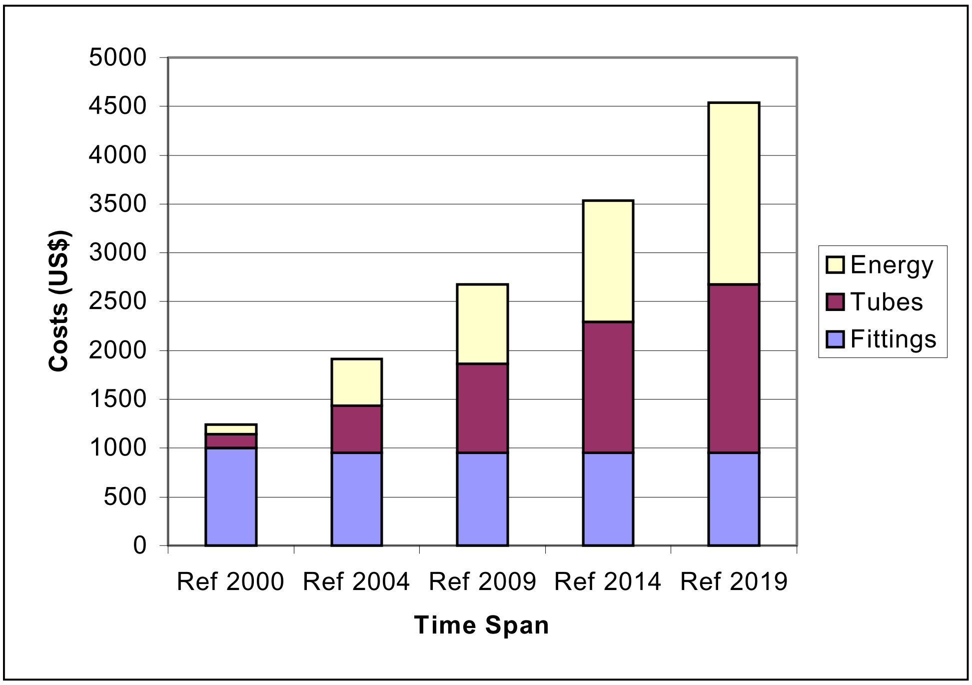


Figure 8-12 LCC Analysis of the Reference Light Fitting System over 20 years

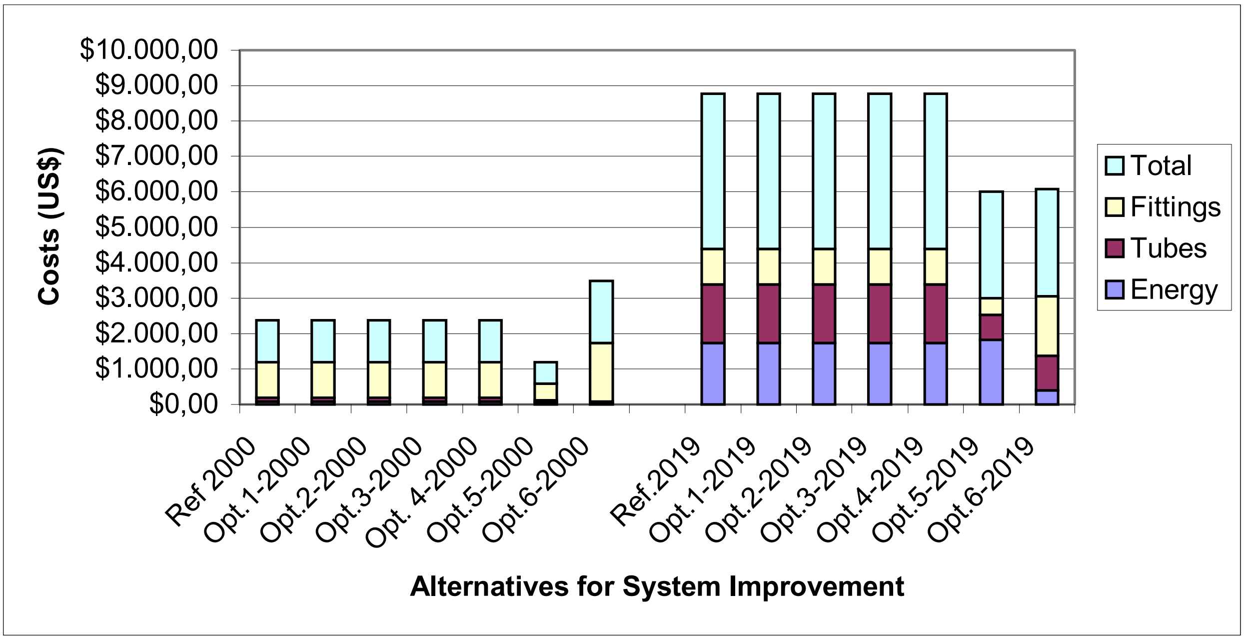


Figure 8-13 Estimated LCC Profiles of the 6 Options for Improvement of Light Fittings

8.6 Quality House (Matrix) of the Light Fitting System

The relationships between customer's quality requirements (including the purchase price) versus the product structure of the light fitting system, which were provided by the company, are presented in Table 8-2 (see also section 7.4). Table 8-2 describes the prioritised customer requirements in relation to the light fittings' product structure. The determination of components' technical ratings provides information on which parts of the product structure

Table 8-2 Customers' Product Quality Matrix of the Reference Light Fitting System

Product Structure	Acrylic Diffuser	Reflec -tor	Plastic Plugs	Alu-Zinc main body	ABS end cap	Ter-minal block	Reactor/ Ballast	Light Tube	Energy conserving equipment	Valuation
Customer Requirements										
Simple surface structure (Easy to wash)	+	o	o	+	+	o	o	o	o	3
Simple and functional design	+	o	o	+	+	o	o	o	o	4
Simple to install in the office	+	+	o	-	o	+	-	o	-	2
Easy to remove plastic cover (easy to change light tubes)	+	o	o	+	o	o	o	o	o	3
Stable luminance, without irritating sharp light	+	+	o	o	o	o	o	+	o	4
Resistance towards humidity	+	o	+	+	+	o	o	o	o	5
High level of anti-corrosiveness in exposed environments	+	+	+	+	+	o	o	o	o	2
Low purchasing price	o	-	o	o	o	o	-	o	-	5
Component's Technical Rating	222	122	126	182	168	96	70	108	70	

Legend:

+	Indicates positive relation and equivalent to 9 points. This means that quality improvement of a product component contributes positively to the satisfaction of customer's requirement.
o	Signifies no or weak relationship and equivalent to 3 points.
-	Denotes negative relation and equivalent to 1 point. This means that quality improvement of a product component contributes negatively to the satisfaction of customer's requirement.

contribute significantly to product system improvements and eventually to the satisfaction of the most important customer requirements. For the calculation of technical rating, one may replace the + *sign by* 9, *o sign with 3* and – *sign with 1* that are used in the relationship matrix so that one can get the technical rating of a product component with regard to all customers' requirements considered. This is accomplished by simply multiplying the equivalent value of the relationship between requirement and the product component and the importance value of requirement and finally adding the values in each column to get the total technical rating. Through this computation of technical rating, one can maximise the satisfaction of customers' requirements by determining those parts that require critical attention.

The most important customer requirements for the light fittings are its ability to withstand a humid environment, low purchasing price, simple and functional design, and also stable luminance. As indicated in the above figure, a quality improvement of the acrylic diffuser contributes positively and substantially to the satisfaction of the critical customer requirements except the cost consideration. Improvements to be made in acrylic diffuser, plastic plugs, aluzinc main body and ABS end-caps will also lead to a positive contribution to the satisfaction of the requirement of "resistance towards humidity". The four important product components that have to be addressed critically to maximise the satisfaction of the customer requirements are: (1) acrylic diffuser, (2) aluzinc-main body, (3) ABS end-caps and (4) plastic plugs. Data on the trade-offs between the quality improvements of the product components is not available, which results to the exclusion of the top triangular shaped-portion of the quality house.

8.7 Alternative Product Concepts for System Improvement

Using the environmental, quality and cost requirements' information based from the streamlined and/or modified QFD, LCA and LCC methods, concepts were generated to improve the baseline product or to come up with a new and more sustainable product system. For example, a new product should have 30% lower weight, 60% higher energy efficiency, 25% better life efficiency, 40% lower life cycle costs, 50% lower fossil fuel consumption throughout the life cycle, and 40% lower contribution to acidification throughout the life cycle compared than the reference product system. Through group brainstorming, options for improving the light fitting system are generated systematically.

The following are the innovative and mutually exclusive options for system improvement that were identified and pre-defined by the product development team (composed of 7 members from different departments) of Lumilight Electric Product and Lighting Inc.

- New product design that reduces the material consumption by 30%, which is easier to disassemble for recovery of materials. This alternative will also considerably lessen the environmental load of the light fitting system as the annual production output runs up to 100,000 units.

- Substitution of aluzinc with black iron in the main body of light fitting system
- Replacement of 70% of the raw aluminium and steel with recycled materials, which reduces the discharges from the production of the light fittings' components.
- Introduction of a system for recovery and post-consumption recycling of the heaviest component materials that reduces the discharges from the production of components.
- Changing the light fittings from 10 W to 20 W. This reduces the needed number of light fittings from 12 to 6 fittings to comply with the reference product's functional unit. It decreases energy consumption in the user phase by using 6 light fittings of 2 X 20 W instead of 12 light fittings of 2 X 10 W. It is assumed that two reactors are necessary per light fitting system. According to Lumilight, the material consumption remains the same as that of the reference product system except for the end caps, and the number of light fittings can be reduced by a factor of 2.
- Changing the light fittings from 10 W to 40 W. This reduces the needed number of light fittings from 12 to 4 fittings to comply with the reference product's functional unit. It decreases energy consumption in the user phase by using 4 light fitting systems of 2 X 40 W instead of 12 light fittings of 2 X 10 W. It compensates for the increase in number of reactors from 1 to 2. According to Lumilight, the material consumption can be reduced by a factor of 0.83 while the number of light fittings by 2/3.
- Adding energy conserving equipment (infrared switch, daylight switch, modern electronic reactors, etc.) to the reference product. In this alternative, electronic ballast or electronic control gear is installed in all light fittings to increase light output and decrease loss of heat. In addition, a daylight detector (that controls the electric light according to one's need) and a person are needed for implementation. This could lessen the energy consumption at most 75% compared when using the reference product system itself.

In summary, the identified product system concept alternatives that are available to product development team are tabulated in Table 8-3. However, it should be noted that the new proposed concepts for improvement might be significantly different from the reference product system with regard to their material composition, material consumption, life span, efficiency in use, quality, cost, and environmental performance, etc.

Table 8-3 Options for Improvement of Light Fitting System

Option Name	Description
Option 1	New product solution with lower material consumption
Option 2	Substitute aluzinc with black iron
Option 3	Replace Al & steel with recycled materials in the product
Option 4	Introduce system for recovery & post consumption recycling
Option 5	Change to higher wattage lighting systems (e.g. 2 X 20 W or 2 X 40 W)
Option 6	Use of energy conserving equipments connected to the armature

8.8 Sustainable Concept Comparison Matrix of Light Fitting System

The sustainable product concept comparison matrix or house shows the relationships between the proposed options for improvement of the light fitting system versus the environmental, economic, and customer's quality attributes. This matrix assists in making a multi-attribute decision to select which concept for product system improvement will be adopted for further implementation. This matrix was thoroughly discussed in sections 7.6 and 7.7.

In the process of evaluating which product system improvement concept should be adopted, the product development team assigns priorities to its chosen criteria. According to the heuristic algorithm developed in Chapter 7, these priorities are assessed linguistically by selecting values of the variable $X = IMPORTANCE$. To rate the *Importance* of each criterion for improvement, Table 8-4 provides the linguistic values or terms to be used.

Table 8-4 Linguistic Terms Used for Importance of Attributes

Linguistic Rating	Description
IC	Indeed Critical
C	Critical
MLC	More or Less Critical
VI	Very Important
I	Important
MLI	More or Less Important
NI	Not Important
U	Unimportant

The environmental, quality, and economic requirements used in this case study which are extracted from the Tables 8-1 and 8-2 and Figure 8-13, and their assessed importance to the overall sustainability strategy are displayed in Table 8-5.

Since the options are also identified as presented in Table 8-3, the capability of each option to achieve each of the common set of criteria can also be established such as shown in Table 8-7.

The effectiveness of each option is assessed by use of values of the linguistic variable *Y* = *CAPABILITY*. To rate the ***Capability*** of each option for improvement to satisfy each of the criteria, Table 8-6 provides the linguistic values to be used.

Table 8-5 Linguistic Assessment of the Importance of each Identified Requirement

Criteria/Attributes for Improvement	Assigned Names	Linguistic assessment (variable value)
Quality Considerations		
Simple surface structure (Easy to wash)	QR1	IC
Simple and functional design	QR2	C
Simple to install in the office	QR3	VI
Easy to remove plastic cover (easy to change light tubes)	QR4	MLC
Stable luminance, without irritating sharp light	QR5	C
Resistance towards humidity	QR6	IC
High level of anti corrosiveness in exposed environments	QR7	VI
Cost Considerations		
Low purchasing price	CR1	IC
Low life cycle costs	CR2	MLC
Environmental Considerations		
Reduced global warming potential	ER1	IC
Reduced acidification potential	ER2	IC
Reduced conversion of fossil fuels	ER3	IC
Reduced impairment of maritime environment (PAH)	ER4	C
Reduced photochemical oxidation potential	ER5	C
Reduced Nutrification Potential	ER6	C
Reduced Humantoxicity	ER7	IC
Reduced Ecotoxicity of Air	ER8	C

Table 8-6 Linguistic Terms of Capability of Options Used

Linguistic Rating	Description
IS	Indeed Superior
S	Superior
MLS	More or Less Superior
AA	Above Average
A	Average
BA	Below Average
P	Poor
VP	Very Poor

The complete sustainable concept comparison matrix or house of light fitting system, as provided by the said company, is shown in Table 8-7. This matrix shows the relationships between the different proposed concepts for improving the original reference product system

Table 8-7 Sustainable Concept Comparison Matrix

		Criteria for Improvement																
		Quality Requirements							Cost Requirements		Environmental Requirements							
		QR1	QR2	QR3	QR4	QR5	QR6	QR7	CR1	CR2	ER1	ER2	ER3	ER4	ER5	ER6	ER7	ER8
Options for System Improvement	Option 1	***MLS***	***MLS***	***S***	***MLS***	***MLS***	***MLS***	***MLS***	***S***	***S***	***S***	***MLS***	***S***	***MLS***	***MLS***	***S***	***MLS***	***MLS***
	Option 2	***MLS***	***MLS***	***MLS***	***MLS***	***MLS***	***BA***	***BA***	***S***	***S***	***S***	***AA***	***S***	***MLS***	***MLS***	***MLS***	***AA***	***AA***
	Option 3	***MLS***	***MLS***	***MLS***	***MLS***	***MLS***	***BA***	***BA***	***S***	***S***	***S***	***AA***	***S***	***S***	***MLS***	***MLS***	***AA***	***AA***
	Option 4	***MLS***	***MLS***	***MLS***	***MLS***	***MLS***	***MLS***	***MLS***	***AA***	***AA***	***S***	***S***	***S***	***S***	***MLS***	***S***	***S***	***S***
	Option 5	***MLS***	***AA***	***AA***	***MLS***	***MLS***	***MLS***	***MLS***	***IS***	***S***	***IS***	***S***	***IS***	***MLS***	***MLS***	***AA***	***MLS***	***MLS***
	Option 6	***MLS***	***MLS***	***AA***	***MLS***	***MLS***	***MLS***	***MLS***	***A***	***IS***	***IS***	***IS***	***IS***	***MLS***	***MLS***	***IS***	***IS***	***IS***
	Importance	**IC**	**C**	**VI**	**MLC**	**C**	**IC**	**VI**	**IC**	**MLC**	**IC**	**IC**	**IC**	**C**	**C**	**C**	**IC**	**C**

Legend: (1) Linguistic Values of Importance, **IC**= Indeed Critical; **C**= Critical; **MLC**= More or Less Critical; **VI** = Very Important; **I**= Important; **MLI**= More or Less Important; **NI**= Not Important; **U** = Unimportant

(2) Linguistic Values of Capability, ***IS***= Indeed Superior; ***S***= Superior; ***MLS***= More or Less Superior; ***AA*** = Above Average; ***A***= Average; ***BA***= Below Average; ***P***= Poor; ***VP*** = Very Poor

(3) **QR** =Quality Requirement; **CR** =Cost Requirement; **ER** = Environmental Requirement

Note: Description of Requirements in Table 8-5 and of Options in Table 8-3.

versus the customer's product quality, environmental and cost attributes, and also the assessed importance of these attributes.

8.9 Calculation for the Selection of a Sustainable Light Fitting System Using the Proposed Algorithm

In this section, the selection of a sustainable product improvement proposal is demonstrated through the use of the proposed heuristic algorithm.

Step 1

Following the steps of the procedure, the *importance* of each of the environmental, quality and cost attributes and the capability of each proposed option for sustainable product improvement to meet each requirement are obtained. The complete sustainable concept comparison matrix is shown in Table 8-7. In this matrix, there are 17 criteria and 6 alternatives with 8 linguistic values for Importance and another 8 linguistic values for Capability. The membership functions of the linguistic values of Importance and Capability are in the form of 1 X 11 array of numbers as shown in Tables 7-1, 7-2, 7-3 and 7-4.

Step 2

Suppose one wants to solve the relative hamming distance of *Alternative 1* which is to develop a new product solution with lower material consumption. Take for instance, the environmental criterion of reducing the global warming potential, *Criterion 10*. According to Table 8-7, the capability of *Alternative 1* to satisfy the given environmental criterion is "*Superior*" and the importance of this *Criterion 10* is "*Indeed Critical*". The relationship between the capability of Option 1 to meet requirement and the importance of criterion of "reduced global warming potential" is expressed by the binary fuzzy relation $r_{x_{10}y_{110}}$, which is shown below:

$$\mu_{M(r_{x_{10}y_{110}})}(u_x,u_y)=\begin{bmatrix}0\\0\\0\\0\\0\\0\\0\\0.10\\0.30\\0.90\\1.0\end{bmatrix}\quad\Theta\quad\begin{bmatrix}0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0.05 & 0.92 & 1.0\end{bmatrix}$$

$$\mu_{M(r_{x_{10}y_{110}})}(u_x,u_y)=\begin{bmatrix}1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 1.00 & 1.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 1.00 & 1.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 1.00 & 1.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.92 & 1.00\end{bmatrix}$$

In a similar fashion, the fuzzy relations representing the 102 entries in Table 8-7 are also computed to complete step 2. When this step is finished, Table 8-7 can be thought of as a 6 X 17 matrix of options of improvements and criteria, with the meaning of each element represented by 11 X 11 fuzzy relation, $r_{x_i y_{ji}}$.

Step 3

In this step, the minimums of the fuzzy relations computed in step 2 are formed across the seventeen attributes for each of the six options for improvement using equation (76). For example, the intersection R_j of the fuzzy relations associated with $j=1$ which is the development of new product solution with lower material consumption across the 17 criteria is:

$$\mu_{M(R_1)}(u_x,u_y)=\begin{bmatrix}1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00\\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00\end{bmatrix}$$

In similar way, the membership functions of R_j's for other alternatives for system improvement can also be determined.

Step 4

Suppose the *IMPORTANCE* of implementing the overall sustainability strategy to the company's future is assessed as x^* = *Indeed Critical*. This value of the linguistic variable was selected because at any phase of the strategic planning process, decision makers want that the satisfaction of stakeholders' requirements be maximised. The meaning of the `ideal` value of x^* = Indeed Critical given in Table 7-3 of the previous chapter.

$$\mu_{M(x^*)}(u_x) = \begin{bmatrix} 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.01 & 0.05 & 0.92 & 1.0 \end{bmatrix}$$

Step 5

Solve the fuzzy relation equation using equation (78) for each option for improvement *j=1,2...n*, to determine the over-all *CAPABILITY* of each alternative to implement the sustainability strategy of the company. For example, the membership function of the overall capability of *Alternative 1* (*j=1*) to implement the sustainability strategy is found to be:

$$\mu^{-1}_{M(y_1)}(u_y) = \begin{bmatrix} 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.01 & 0.05 & 0.01 & 0.00 \end{bmatrix} \Theta \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.01 \\ 0.05 \\ 0.92 \\ 1.0 \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \\ 1.0 \\ 1.0 \\ 1.0 \\ 1.0 \end{bmatrix}$$

so

$$\mu_{M(y_1)}(u_y) = \begin{bmatrix} 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 1.00 & 1.00 & 1.00 \end{bmatrix} \quad for\ j = 1$$

Similar calculations to find the compatibility functions for the remaining alternatives are as follows:

$$\mu_{M(y_2)}(u_y) = [0.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00]\quad for\ j = 2$$

$$\mu_{M(y_3)}(u_y) = [0.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00]\quad for\ j = 3$$

$$\mu_{M(y_4)}(u_y) = [0.00\quad 0.05\quad 0.05\quad 0.92\quad 0.92\quad 1.00\quad 0.92\quad 1.00\quad 1.00\quad 1.00\quad 1.00]\quad for\ j = 4$$

$$\mu_{M(y_5)}(u_y) = [0.00\quad 0.01\quad 0.01\quad 0.01\quad 0.01\quad 0.01\quad 0.01\quad 1.00\quad 1.00\quad 1.00\quad 1.00]\quad for\ j = 5$$

$$\mu_{M(y_6)}(u_y) = [0.00\quad 0.05\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00\quad 1.00]\quad for\ j = 6$$

Step 6

None of the compatibility functions computed in step 5 are defined in Tables 7-2 and 7-4. That is, the linguistic values that they define them are not apparent. However, one may use these compatibility functions to determine the most sustainable proposal by computing the relative Hamming distance of the calculated compatibility function of Alternative 1 (in step 5) from the ′ideal′ compatibility function y* = *Indeed Superior*, whose compatibility function is given in Table 7-4 (found in the previous chapter). This is shown below.

$$\mu_{M(y^*)}(u_y) = [0.0\quad 0.0\quad 0.0\quad 0.0\quad 0.0\quad 0.0\quad 0.0\quad 0.02\quad 0.18\quad 0.98\quad 1.0]$$

$$\begin{aligned}\delta_1 &= \frac{1}{11}\big[|0-0|+|0-0|+|0-0|+|0-0|+|0-0|+|0-0|+|0-0|+|1-0.02|+|1-0.18|+|1-0.98|+|1-1|\big]\\ &= 0.1655\end{aligned}$$

Similar steps can be followed in the calculation of relative hamming distance for the other options for system improvement.

Step 7

The complete results are presented in Table 9-1 of the next chapter. With these tabulated results, one can choose the option with the minimum relative hamming distance as the most sustainable and optimal one to pursue.

9 Results, Analysis and Discussion

The main result is the developed conceptual methodology as discussed in Chapter 7. Specific to the case study or the application of the approach, its results, sensitivity and statistical analyses and discussion are presented and explained here in detail. For the analysis of the results of the case study, a few sensitivity analyses were conducted such as replacing the array of "Importance" linguistic values of the requirements, or altering the linguistic values of the "Capability" of each option to satisfy each requirement, or changing the ideal over-all value for "Importance" of implementing the sustainability strategy to the future of the company, or varying the ideal over-all value for "Capability" by any option for system improvement. In addition to this "what-if" analysis, both one-factorial analyses of variance (ANOVA) and two-factorial ANOVA without replication were performed to check the null hypothesis (H_0) that the ranks of the considered options for system improvement, which are based on their expected means of relative Hamming distance, are the same. These two analyses aid to confirm the ranking obtained.

9.1 Ranking and Selection of Options for Improvement of Light Fitting System

The ranking results shown in the succeeding tables (Tables 9-1 to 9-7) below were obtained by setting the ideal over-all values for Importance at ***"Indeed critical"*** and for Capability at ***"Indeed Superior"***. The calculation of relative hamming distance was shown in section 8.9. The lower the relative hamming distance, as explained in steps 6 and 7 of the developed algorithm in section 7.8, the better its rank and thus it is more preferred by the decision makers. For example, as shown in Table 9-1 below, Option 1 is better than Option 5 which is in turn better than Option 4 because the relative hamming distance of Option 1 < Option 5 < Option 4. Thus, Option 1 is set as rank 1, Option 5 as rank 2, Option 4 as rank 3 and so on. To reiterate, the options for improvement considered are: Option 1 (New product development with lower material consumption); Option 2 (Substitution of Al-Zn with black iron); Option 3 (Replacement of Aluminium and steel with recycled materials); Option 4 (Introduction of system for recovery and post-consumption recycling); Option 5 (Change to higher wattage lighting systems) and lastly, Option 6 (Usage of energy conserving equipments connected to the armature).

In the succeeding sections, the best or optimal options for system improvement among environmental, quality and cost criteria, between environmental and cost attributes, between environmental and quality criteria, between quality and cost requirements and also with respect to the individual attributes are reported.

9.1.1 Assessment Based on Product Quality, Environmental and Cost Considerations

Table 9-1 illustrates the most important outcome of the case study where the ranking is based on the simultaneous consideration of customer product quality, environmental and cost requirements. As shown in the table below, Option 1 is the most sustainable concept for a system improvement because its capability in meeting relevant environmental, cost and quality requirements are at least more or less superior which translates into low relative hamming distance. If one reviews all the subsequent tables in this chapter, this product system improvement concept always positions itself closer to the most preferred alternative and performs well across the critical requirements. It is closely followed by Option 5 and then by Option 4. Option 6 placed fourth in the ordering where its superiority lies specifically to its environmental performance. The least preferred options are Option 2 and Option 3. For these two last options, one may become indifferent but fortunately they have found to be non-preferred alternatives. Their weak capabilities to meet the quality, cost and environmental requirements simultaneously are similar to their individual effectiveness as demonstrated in the other assessments made below. Despite the results in Table 9-1 looks acceptable, the ranking result is more reliable if more runs are made and sensitivity analyses are conducted. In section 9.2, results of the scenario analyses are presented to know how the ranking of these alternatives might change.

Table 9-1 Ranking based on Customer Product Quality, Environmental and Cost Considerations

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1655	1
2	0.7109	5
3	0.7109	5
4	0.5164	3
5	0.1709	2
6	0.6246	4

9.1.2 Assessment Based on Environmental Consideration

In Table 9-2 below, the best option for improvement with respect to environmental attributes alone is Option 6. This is the option that recommends the use of energy conserving equipments to be connected to the armature of the light fitting system. The selection of this alternative can also be deduced from the estimated environmental performances of options for system improvement in the green matrix (Table 8-1) as illustrated in the preceding chapter. As indicated in Chapter 8, since the user phase of the product life cycle shows to have the greatest potential for environmental performance improvement, this option can effectively and significantly address the environmental improvement of the reference product system. Secondly, Option 6 has *indeed superior* capability in comparison with any other options in addressing the critical environmental requirements of light fitting system. Next, this is followed by Option 4 and Option 1. Option 5 closely follows them. Although all these considered options involve some sort of environmental improvement, the least preferred alternatives in this category are Option 2 and Option 3.

Table 9-2 Ranking based on Environmental Considerations

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1509	2
2	0.5018	4
3	0.5018	4
4	0.1509	2
5	0.1564	3
6	0.0718	1

9.1.3 Assessment Based on Customer's Product Quality Considerations

In Table 9-3 below, the ranking with respect to product quality attributes alone results to Option 4, Option 1 and Option 6 as best alternatives. These three alternatives show at least more or less superior capability in satisfying most of the quality requirements of the customers, particularly the critical ones. Option 5 follows them closely. Lastly, the least preferred alternative with respect to quality criteria is shared equally by Option 2 and Option 3. These two last alternatives are least preferred because they have below average effectiveness in meeting the critical quality requirement of resistance towards humidity and were further gravitated by their below average capability to meet the very important requirement of high level of anti-corrosiveness in exposed environments.

Table 9-3 Ranking based on Customer's Product Quality Considerations

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1655	1
2	0.7109	3
3	0.7109	3
4	0.1655	1
5	0.1709	2
6	0.1655	1

9.1.4 Assessment Based on Cost Consideration

As illustrated in Table 9-4 below, when the evaluation is based on cost consideration, the alternative that proposes the use of energy conserving equipment to be connected into the armature is the most expensive one because of its additional cost of installing a switch, daylight detector and employing one extra person. However this option might be cheaper when the whole 20-year period is considered because of its better operating efficiency, which consequently results to lesser total energy consumption costs. Option 5 that suggests a change to higher wattage armature system, for instance, from 2 X 10 W to 2 X 20 or 2 X 40 W, is the most preferred option. In this system improvement concept, it is only necessary to install either 6 of 2 X 20 or 4 of 2 X 40 fitting systems instead of 12 original systems to fulfil the functional unit. Option 5 involves low purchasing costs in the first year although its long-term cost might be just similar to Option 6. So, in a long-term horizon, Option 6 and Option 5 might have the same incurred life cycle costs. Indifference in ranking among Option 1, Options 2, and Option 3 are encountered. Option 4 ranks third in terms of cost aspect.

9.1.5 Assessment Based on Environmental and Cost Considerations

Table 9-5 below presents the result when the options for improvement are assessed with consideration to both environmental and cost attributes. The most preferred concept is Option 1 because it satisfies the critical environmental requirements of reduced global warming potential, reduced acidification potential and reduced conversion of fossil fuels and the cost requirement at a capability, which is at least more or less superior. Option 5 follows it closely. Options 2, 3 and 4 have similar relative hamming distances and rank third. Option 6 is the least preferred which is being pulled down by its high initial purchasing cost involvement although it improves the environmental performance of the light fitting system the most.

Table 9-4 Ranking based on Cost Consideration

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1509	2
2	0.1509	2
3	0.1509	2
4	0.62	3
5	0.0718	1
6	0.7536	4

Table 9-5 Ranking based on Environmental and Cost Considerations

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1509	1
2	0.5018	3
3	0.5018	3
4	0.5018	3
5	0.1564	2
6	0.5809	4

9.1.6 Assessment Based on Product Quality and Environmental Considerations

As displayed in Table 9-6, Option 6 ranks equally with Option 4 and Option 1 at the first position because they have at least above average capability in meeting majority of the quality and environmental requirements of the light fitting system, which eventually leads to low relative hamming distance as compared to other alternatives. Options 1 and 4 have more or less similar capabilities with respect to environmental and quality aspects. Option 6, on the other hand, has only an above average capability to satisfy the very important quality requirement of simple to install in the office, however, this is compensated by its indeed superior effectiveness to meet the critical environmental requirements of light fittings.

Option 5 ranks second and follows the preferred alternatives closely. The least preferred system improvement concepts within this consideration are Option 2 and Option 3. The weak preference of these latter options is due to their below average capability to satisfy the ***indeed critical*** requirement of "resistance towards humidity" and the ***very important*** requirement of high level of anti-corrosiveness in exposed environments in spite of their at least above average performance in meeting the environmental requirements of light fitting system. As a result, these options have high relative hamming distances in comparison to others. Another observation with regard to Option 2 is that, it is frequently closer to the least preferred option as demonstrated in the case when the alternatives for system improvement were assessed with regard to environmental and cost performance.

Table 9-6 Ranking based on Product Quality and Environmental Considerations

Options for System Improvement (j)	Relative Hamming Distance (δ_j)	Rank
1	0.1655	1
2	0.7109	3
3	0.7109	3
4	0.1655	1
5	0.1709	2
6	0.1655	1

9.1.7 Assessment Based on Product Quality and Cost Considerations

With respect to product quality and cost considerations, as shown in Table 9-7, Option 1 is the most preferred alternative. Its superiority is demonstrated by its superior capability to meet the cost requirements and at least more or less superior effectiveness in satisfying the product quality expectations of the customers. Option 5 ranks second and follows Option 1 closely. Option 4 ranks third and Option 6 ranks fourth. Option 2 and Option 3 show similar weak effectiveness in their product quality and cost performance that translates to high relative hamming distance and again are the least preferred alternatives.

Table 9-7 Ranking based on Product Quality and Cost Considerations

Options for System Improvement (j)	Relative Hamming Distance, (δ_j)	Rank
1	0.1655	1
2	0.7109	5
3	0.7109	5
4	0.5164	3
5	0.1709	2
6	0.6246	4

9.2 Closer Examination of the Ranking based on Quality, Environmental and Cost Requirements

Although it is interesting to conduct sensitivity analyses for all the assessments reported above, only the sensitivity analyses of ranking result in Table 9-1 were performed because it is the most important output of the case study. Many researchers in product development have recommended that the more time spent in productively evaluating competing concepts, the shorter will be the total design time and the better the product will be at the end. Thus, additional runs were made. Figures 9-1 to 9-4 show the diagrams of the sensitivity analyses conducted. To understand these figures, one should remember that the closer the option to the left of the diagram, the better its rank among the options. However, when the options have the same relative hamming distances, they appear at the same level since they have the same rank. Although the figures below also show the relative hamming distances of the alternatives, which represent the performance measure of an option for system improvement, the exact values of these distances are not important because one is only interested on the order of the options just like in any ranking results of multi-criteria studies. The reference scenario is based on Table 9-1.

9.2.1 Scenario 1: Changing Assumed Ideal Linguistic Value of "Capability"

First, the ideal over-all linguistic value for "Capability" was changed from *indeed superior* to *superior* and then to *more or less superior.* The change of over-all linguistic value of " Capability" was only limited to the linguistic value "More or Less Superior" because one is only interested on maximising the effectiveness of an option to achieve the ideal characteristics. Using the same linguistic data as shown in Table 8-7, the ranking result is shown in Figure 9-1. This figure shows that there is no change in ranking order in comparison to the reference scenario's ordering when the ideal over-all value of "Capability" was altered. Option 1 is still the best alternative while Options 3 and 2 are the least preferred ones.

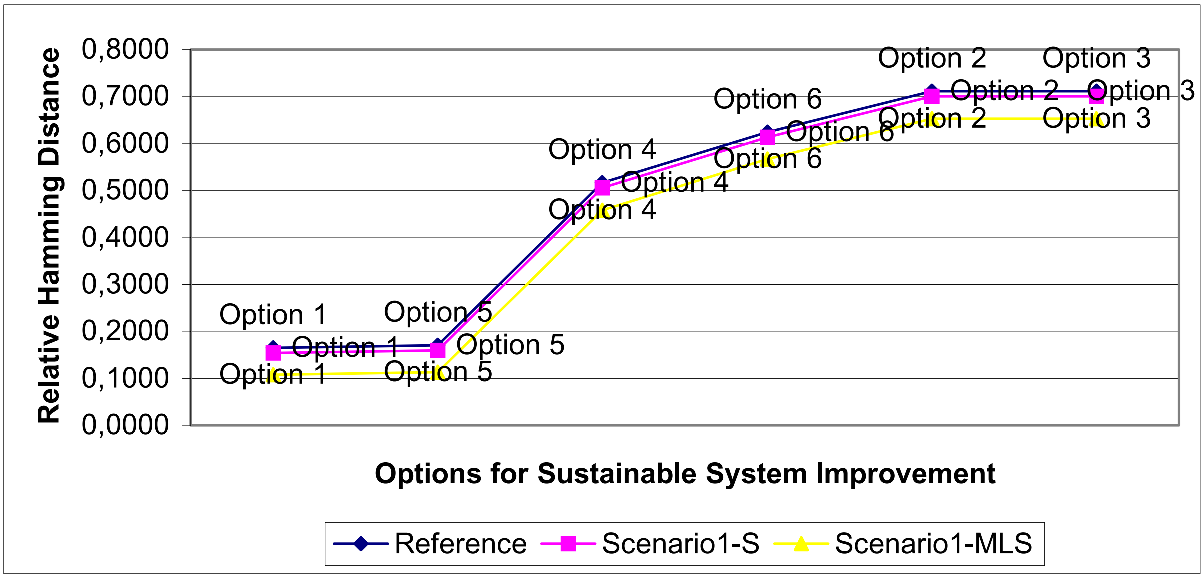


Figure 9-1 Sensitivity Analysis Results when Changing the Assumed Ideal Over-all Values of "Capability"

9.2.2 Scenario 2: Changing Assumed Ideal Linguistic Value of "Importance"

Second, the ideal linguistic value for "Importance" of implementing the overall sustainability strategy to the future of the company was changed from ***indeed critical to critical*** and then ***more or less critical***. Using the same linguistic data as presented in Table 8-7, the ordering is shown in Figure 9-2. At this time, there is a rank reversal between Options 4 and 5 when the ideal over-all linguistic value was changed from indeed critical to critical. Option 1 is still the preferred choice. The ordering of the other options remains the same as compared to the reference scenario, e.g. the least preferred Options 3 and 2. Similar ranking was observed when the ideal value of "Importance" was changed to more or less critical.

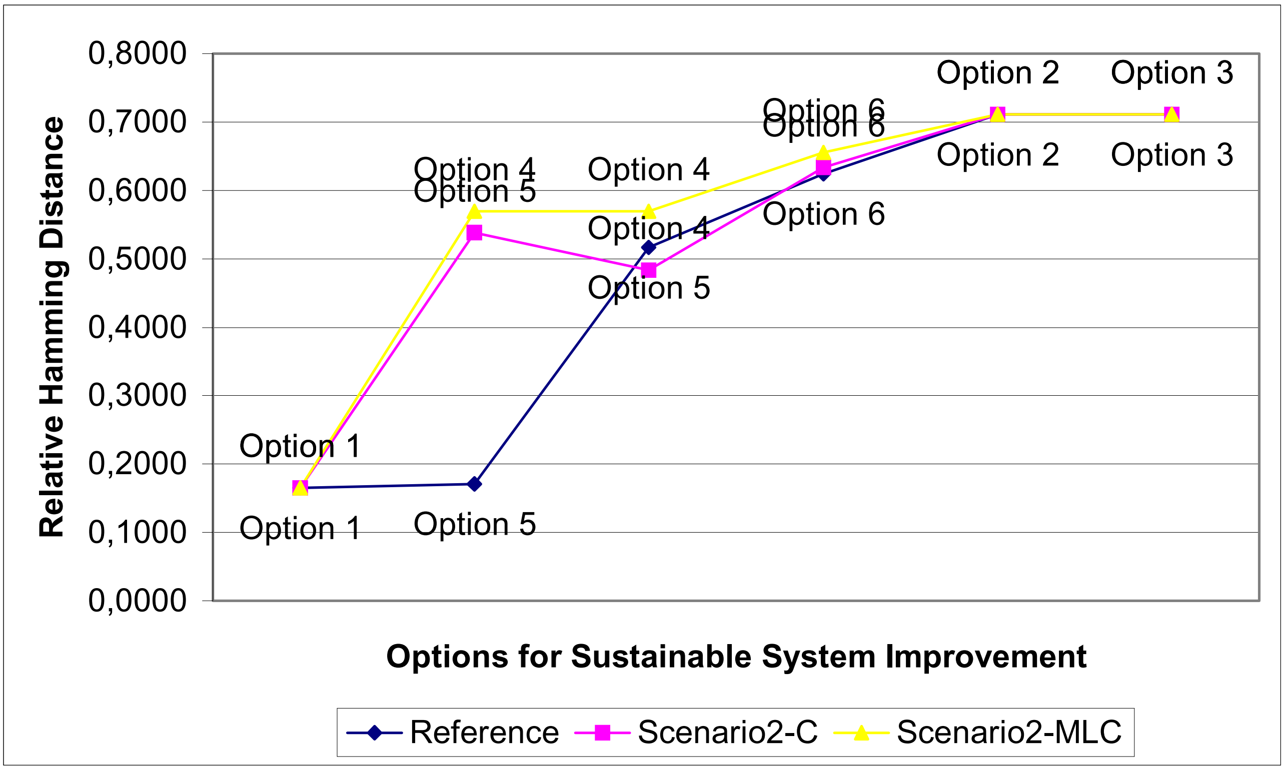


Figure 9-2 Sensitivity Analysis Results when Changing the Assumed Ideal Over-all Value of "Importance"

9.2.3 Scenario 3: Replacing the Linguistic Values in the Original 1 X 17 "Importance" Vector

Third, this scenario analysis is accomplished by degrading the "Importance" of a criterion by one step below of its original linguistic value. For example, if the linguistic value of "Importance" of criterion 1 is originally set at *Indeed Critical* in the original matrix (Table 8-7), then this is replaced by *"Critical"* as its current linguistic value. However the over-all ideal values for ***Capability*** and ***Importance*** remain the same, *Indeed Superior and Indeed Critical*, respectively. As shown in Figure 9-3, there is no reversal in ranking as compared to the ranking of the reference scenario. Option 1 is still the best option and it is directly followed by Option 5. Option 2 and Option 3 are still the least preferred ones.

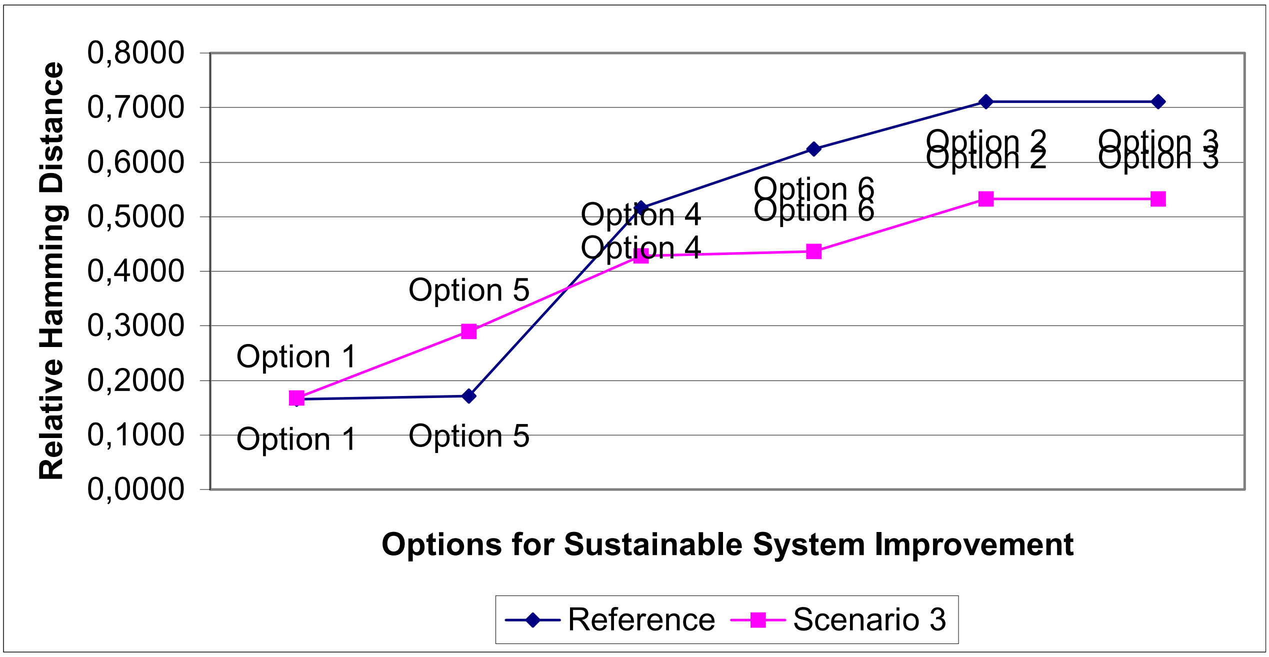


Figure 9-3 Sensitivity Analysis Results when Changing the Linguistic Values of the "Importance" Vector

9.2.4 Scenario 4: Replacing the Linguistic Values in the Original 6 X 17 "Capability" Array

Fourth, this scenario analysis is realised by degrading the "Capability" of an option to meet a particular requirement by one step below of its original linguistic value. For example, if the linguistic value of the *Capability* of Option 1 to satisfy attribute 1 is *More or Less Superior*, then this is replaced by *"Above average"* as its current value. However the over-all ideal linguistic values for ***Capability*** and ***Importance*** are held constant, e.g. *Indeed Superior and Indeed Critical*, respectively. Figure 9-4 shows that the ordering of options for system improvement was slightly affected by the change in the linguistic values used in the original "Capability" matrix. Option 5 ranks equally with Option 1 and both are considered best choices. This signifies that one becomes indifferent between Options 1 and 5. The ranks of the other options remain the same.

As indicated in Figures 9-1 to 9-4, Option 2 (substituting aluzinc with black iron) and Option 3 (using recycled materials in the product) are definitely the least preferred alternatives. Thus, it does not refute the conjecture that these two last options should not be adopted or even implemented at all.

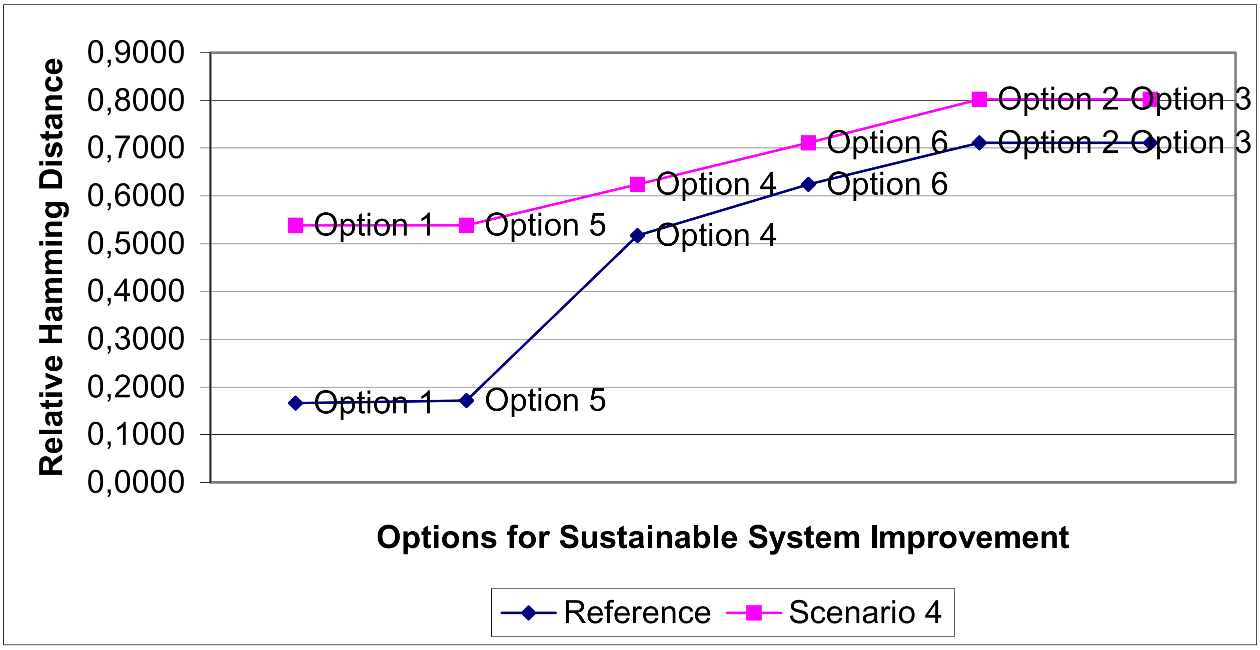


Figure 9-4 Sensitivity Analysis Results when Changing Some Linguistic Values in the "Capability" Array

Across the 4 scenarios considered in this case study, the final expected means (averages) of the relative hamming distance of the alternatives were computed to use as basis for the determination of the expected ranking of the options such as shown in Table 9-8. As displayed in this table, the most sustainable and optimal proposed concept for improvement for the light fitting system studied is Option 1, which suggests development of new product system with lower material consumption. This is followed by Option 5 that recommends improvement to change to higher wattage armature systems and then by Option 4 that is introduction of system for recovery and post consumption recycling. Next, Option 6, which is the alternative that proposes the use of energy conserving equipments connected to armature, ranks fourth. Option 2, which is the substitution of aluzinc with black iron, and Option 3, which is to use recycled materials in the product, are the least preferred among the product improvement concepts considered.

Moreover, after doing sensitivity analyses, analysis of variance (ANOVA) is further conducted to check statistically the established ranking of the developed methodology. ANOVA might also aid to break the indifference between Option 2 and Option 3 or between Option 1 and Option 5 in some assessments made above. This analysis is done by setting the null hypothesis (H_o) that the options for system improvement have equal ranks. In other words, it is examined here whether the expected means (averages) of relative hamming distances of the alternatives are the same within a given alpha value or level of significance. This is discussed next.

Table 9-8 Expected Ranking of Options for System Improvement

Options for System Improvement, j	Expected Mean of Relative Hamming Distance, $\bar{\delta}_j$	Expected Rank
1	0.2092	1
2	0.6886	5
3	0.6886	5
4	0.5123	3
5	0.3398	2
6	0.6058	4

9.3 Statistical Analysis of Ranking Results

As illustrated in the previous tables and figures of the preceding sections, it is observed that there are indifferences between the options or similarities in ranking encountered. For instance, indifference in deciding between options 2 and 3 occurred. To address these similarities of ranking, both one-factorial analysis of variance (ANOVA) and two-factorial ANOVA without replication were conducted to find out whether there is reason to believe that equality in ranking exists among the alternatives and between options.

Assuming that the ANOVA test is valid to be applied in the present case study, 95%, 99% and 99.9% confidence level (equal to 0.05, 0.01 and 0.001 alpha values or levels of significance, respectively) were used to test the null hypothesis (H_o) that all the options considered have equal ranks because they have similar expected means of relative Hamming distance. The alternative hypothesis (H_1) is defined that the ranking shown in Table 9-8 is acceptable as true ordering of the options within a given level of significance. For α=0.05 and number of runs made per option, n =27, the one-factorial ANOVA of the 6 choices (see Table 9-9) resulted that there is no reason to believe that the expected ranks of options for system improvement could be the same and thus, the proposed ranking is acceptable. Other tighter values of α's were also used to further test the ordering and similar conclusions were also inferred. As the computed F (Fisher statistic) values are greater than the critical F values across the three levels of significance, it can be concluded again that the proposed expected ranking in Table 9-8 is statistically acceptable.

Table 9-9 One-Factorial ANOVA Results of Ranking

Alpha Values	Computed *F*-value	Critical *F*-value
0.05	22.15	2.27
0.01	22.15	3.14
0.001	22.15	4.34

For the case of 2-factorial analysis of variance (ANOVA) without replication of the 6 options for system improvement, the following results were obtained across the three alpha values as shown in Table 9-10.

Table 9-10 2-Factorial ANOVA Results of Ranking (Without Replication)

Alpha Values	Computed *F*-value	Critical *F*-Value
0.05	64.63	2.28
0.01	64.63	3.16
0.001	64.63	4.39

From the above table of results, at different values of α‘s, it is again found out that the computed *F*-values are greater that the critical *F*-values. Thus, there is reason to reject the null hypothesis and to infer that the proposed expected ranking could be true. This further attested the inference made in the one-factorial ANOVA previously and provided a stronger evidence against H_0 since the effect of differences among scenarios or runs has been netted out.

However, if one delves the similarities in ranking between options and setting the α value at 0.001, it is found out that Options 2 and 3 could really have the same rank because the computed *F*-value (3.25) is less than the critical *F*-value (13.74). This could mean that the decision maker or the product development team itself is indifferent between these two options. Option 1 is found to be superior in the analyses of variance when compared to other options statistically, e.g. between Option 1 and Option 5. Diagrammatically, the final proposed ranking is presented in Figure 9-5. In this figure, an outgoing arrow point means that one option predominates (outranks) another alternative. If there is indifference between the options, there is no point on the arrow (e.g. Option 3 and Option 2).

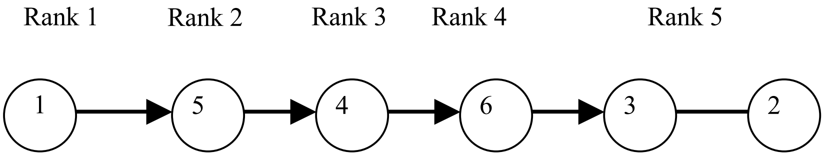


Figure 9-5 Final Proposed Ranking of Options for Sustainable System Improvement

9.4 Summary of Selected Options for System Improvement

The final results of this case study are summarised and reported in Table 9-11 below.

Table 9-11 Summarised Ranking Results at Different Performance Criteria

Attributes/Performance Metrics Used	**Best Option for Improvement of Light Fitting System**
Customers' Product Quality, Environmental and Cost Requirements	Development of new product with lower material consumption
Environmental Requirements	Use of energy conserving equipment connected to the armature
Customers' Product Quality Requirements	Introduce system for recovery and post-consumption recycling of materials; Use of energy conserving equipment connected to the armature; Development of new product with lower material consumption
Cost Requirements	Change to higher wattage armature systems
Environmental and Product Quality Requirements	Introduce system for recovery and post-consumption recycling of materials; Use of energy conserving equipment connected to the armature; Development of new product with lower material consumption
Environmental and Cost Requirements	Development of new product with lower material consumption
Product Quality and Cost Requirements	Development of new product with lower material consumption

From the above table, it is indicated that the option for product system improvement in the case of light fitting system is more or less dependent on the performance criterion or criteria considered. To relate these results to the concept of sustainable competitive advantage, Porter emphasised that to remain competitive, firms should be able to create value for its buyers or other stakeholders that exceeds the cost of creating it. He posited that sustainable competitive advantage could be achieved in 2 ways. One is by cost leadership and the other is by differentiation [Porter, 1985, p.3]. Thereby, the results in Table 9-11 further imply that firms could select which strategy they have to follow either to remain as cost leader and/or also to differentiate their products with respect to quality performance and/or environmental friendliness. If the criterion of the company for its sustainable competitive advantage goal was focused on environmental consideration alone, then the manufacturing firm would prefer to adopt the system improvement that uses energy conserving equipments connected to the armature as their strategy although its initial purchasing cost is high. Moreover, if the intention of the sustainable product improvement project is to select the alternative that considers quality, environmental and cost aspects at the same time, then the option that develops new product with lower material consumption for the purpose of easier disassembly is the most sustainable and satisfactory one to be pursued by the product development team. Despite that this option is only ranked 2nd with respect to individual cost and environmental considerations, it ranks first with other considerations. This optimal system concept of developing a new product with lower material consumption is also in agreement with the philosophy of waste reduction. Reducing the mass of a product through minimising the amount of materials used for key components is the surest and most direct way to achieve waste reduction and this usually results to lower life-cycle costs as well [Fiksel, 1996, p. 10]. This selected concept further agrees to one of the main strategies towards more sustainable activities, which is to innovate new and more environmentally sound products continuously, as put forward by the German Bundestag Enquete Commission on Protection of Environment and the Humanity. Nevertheless, if the product development team prefers to make improvement with respect to cost consideration alone, then changing to higher wattage armature systems, such as 2 X 20 watts where one only needs 6 light fitting systems instead of 12 of 2 X 10 watts, or 2 X 40 watts where one only needs 4 light fitting systems instead of 12 of 2 X 10 watts, is an appropriate and acceptable choice. The results obtained with consideration to environmental, quality and cost factors using the fuzzy linguistic approach are more or less similar to the outcomes obtained by Lumilight Electric Product and Lighting Incorporated using a simulation approach. For instance, the development of new product with lower material consumption was also recommended to be pursued because it did not conflict with any of the customer requirements and scored higher on functional design and easy installation. The use of energy conserving equipment connected to the armature was also found to be the option that will contribute the most significant environmental quality improvements.

Finally, by knowing the optimal or satisficing product system improvement alternative, the cross-functional project team of the manufacturing firm can now allocate the necessary resources to explore extensively the selected alternative for further deployment in the QFD process.

10 Conclusion and Recommendation

In this section, conclusions based on the findings of this study, strengths and weaknesses of the study, implications of the result, research contributions and finally suggestions for future research are discussed.

10.1 Conclusion

The conceptual approach developed in this study that attempts to incorporate environmental, quality and economic requirements at the early stage of product development (with consideration to imprecision of data inputs that influences a product development decision for company's sustainability plan) is distinct by itself and seems promising. This method is appealing and can be an essential means in guiding manufacturers, particularly their product development teams, to make sustainability decisions or even for the sole purpose of exploring the synergistic effect of critical economic, quality and environmental requirements of concerned stakeholders. The key elements of the developed methodology include: (1) life cycle and system approach to product improvements; (2) integrated method with respect to product development, (3) simultaneous consideration of customers' product quality, life cycle economy and environmental requirements; and (4) consideration of imprecise and inadequate information available at the early design stage.

Moreover, it is further indicated in this work that the optimal option for product system improvement, as in the case of light fitting system, is dependent on the performance metric considered. As Porter argued, sustainable competitive advantage could be achieved in 2 ways: (1) cost leadership and (2) differentiation. With relevance to the case study's results, this implies that firms should select a strategy that they have to follow to remain as cost leader and/or also to differentiate their products with respect to quality performance and/or environmental friendliness.

Although the results of the case study largely depend on the availability and precision of data used and the accuracy of the defined fuzzy linguistic values, the methodology developed here is of general in nature and application to both consumer and industrial products. The major weakness of this proposed framework is more in the context of intensive data requirements for LCA, QFD and LCC methods. The translation of the linguistic assessments into fuzzy numbers might also affect the ranking results of the case study made. Additionally, the fuzzy multi-attribute decision making method proposed here is independent of the type of membership functions being used. The inconsistency in decision maker's ratings for "Importance" and "Capability" in the sustainable concept comparison matrix may not be detected as well. Due to these potential weaknesses, the validity of the findings of the case study might only be limited within this research. Conversely, the results of the sensitivity analyses show that the selection of the most sustainable option, as demonstrated in the case study, appears fairly insensitive to specification of the “ideal over-all values” of capability and of importance, to membership function variations and to different linguistic assessment of the importance of the QEC attributes and the capabilities of mutually exclusive sustainable options for system improvement. Additionally, the results obtained with consideration to environmental, quality and cost factors using the fuzzy linguistic approach are more or less similar to the outcomes obtained by the company using a simulation approach. For instance, the development of new product with lower material consumption was also recommended to be pursued because it did not conflict with any of the customer requirements and scored higher on functional design and easy installation. The use of energy conserving equipment connected to the armature was also found to be the option that will contribute the most significant environmental quality improvements. Recently, two separate comparative studies between AHP and fuzzy decision analysis by Italian and Australian researchers reported that the ranking results of these two methods are closely similar the same except that fuzzy decision analysis has many advantages over AHP. Some strengths of the proposed methodology, specific to the fuzzy linguistic decision support system, are: (1) rating system used in the fuzzy linguistic heuristic algorithm is generally considered easy and simple because it uses everyday words to express the exact feeling of rating, (2) no usual or difficult comparisons due to individual factor/attribute ratings as in the case of AHP methodology, (3) there is no limit on the number of factors and the complexity of analysis is not greatly affected by the number of factors.

10.2 Implications

The developed conceptual decision-oriented methodology that accounts for environmental, quality and cost requirements at the early stage of product improvement has the potential to assist in improving a manufacturing enterprise’s competitiveness in the marketplace. Through the use of this approach, manufacturing companies, particularly in the Philippines, will get a better platform for developing long-term environmental and competitive strategies through having knowledge about which environmental problems, customers’ quality and cost issues of a given product system are most significant, and knowing which parts of the system contribute to these aspects. In addition, the design team of an industrial company will be directed towards actions that will result in maximum payoffs.

Likewise, this proposed approach supports decisions, either business decisions by manufacturers or policy decisions by governmental and other organisations. Specifically, this methodology is useful for corporate decision makers who are concerned with cost, quality and environmental aspects in their evaluation and selection of appropriate system to be implemented from a list of potential alternatives. The third phase of this developed approach is not only relevant in improving a product system but also in evaluating technology options and process concepts, selecting the right policy for sustainable industrial development, choosing environmentally conscious techniques or whatever systems with the purpose of achieving sustainability.

10.3 Research Contributions

On the basis of this research work, the main contributions are the following:

(i) It attempts to integrate quality, environmental and cost requirements and account the imprecision and incompleteness of design data inputs at the early stage of product improvement;

(ii) It developed a green matrix or house that aids in the determination of the critical emissions and establishment of environmental requirements and a quality matrix or house that shows the relationships between the customer requirements and product structure;

(iii) It developed a sustainable concept comparison matrix and a fuzzy linguistic based decision algorithm to evaluate the alternatives for sustainable product improvement or development and select the most sustainable and optimal one; and

(iv) It provided companies a holistic and preventive life cycle approach for product system improvement; and

10.4 Suggestions for Further Research

There are many potential extensions of this work. Some of these are the following:

- Since the actual detailed design stage of the product development process or the later deployment of the requirements are not conducted in this work, then this would be an interesting avenue for future research. After having selected which optimal or best option for product system improvement to undertake, then details of the product system can be closely examined. A CAD-CAM software may be used to assist in specifying the selected system design concept. In this phase, the critical requirements of the certain product concept are deployed into product/process design stages so that a series of matrices can be created for design deployment, process planning, production planning, maintenance planning, and retirement planning. Through covering these succeeding stages, one can be assured that the requirements of customers' product quality, environment and cost are tackled throughout the entire product development process.

- Extend the developed heuristic algorithm for the decision support system (DSS) aspect of the methodology to group support system (GSS) to cater the involvement of different managers or decision makers from different divisions for the design of sustainable products and processes as exemplified in the philosophy of concurrent engineering and integrated product development. This might be realised by allowing each decision maker or member of the product development team to have his or her own sustainable concept comparison matrix, whereby he/she expresses his/her individual ratings for importance of requirements and capabilities of alternatives. Once all these constructed matrices are obtained, one can intersect these matrices to form a "group sustainable concept comparison matrix". However, as the number of decision makers, number of criteria or the number of considered options for improvement increases, the intricacy of the study might increase too. As a consequence, this might require the development of appropriate computer programs to do the necessary calculation. By developing an efficient and flexible GSS e.g. hypertext-based group decision support system, effective exchange of information and ideas with experts from different divisions will ensue even though the members of the team will not meet personally and are located in disparate locations.

- The *"Importance"* or the weights of the environmental requirements can be estimated from different considerations such as public opinion on the impact of the product, local environmental effects, sales points to represent the company's marketing policy for the environmental perspective of the product and lastly the benchmarking and improvements made with respect to other competing similar products.

- Simulation can be used to validate the evaluation and selection made in this study. This technique can be used to optimise the best promising product concept (s) for the purpose of increasing the precision of its environmental profile, estimating the values of itemised life cycle cost factors and refining the selected design concept. For example, simulation software called ASPEN Plus might be utilised for process industries while either SIMAN or SIMFACTORY for discrete manufacturing. If in case the suggested simulation softwares are not applicable, then a general simulation programs such as General Purpose Simulation System (GPSS) could be adopted.

- A comparative study between the proposed fuzzy linguistic methodology and the well-known Analytic Hierarchy Process (AHP) method [Noci & Toletti, 2000; Ghotb & Warren, 1995] or any other multi-criteria decision-making (MCDM) methodologies that incorporate fuzziness such as Fuzzy AHP [Leung & Cao, 2000; Kuo, Chi & Kao, 1999] or Fuzzy PROMETHEE [Goumas & Lygerou, 2000; Geldermann et al., 2000] or Fuzzy ELECTRE [Bisdorff, 2000], can be conducted to compare the preference results obtained.

- Develop a new method that integrates LCA, Failure Modes and Effects Analysis (FMEA) and Petri net modelling for the assessment of pollution prevention technologies. FMEA is a proven method and well-used method for predicting complex system and component failures and their effects on system usability and safety. When combined with LCA, FMEA provides the ability to predict system failures and therefore potential requirement for increased material and energy as weel as the potential adverse environmental impacts including pollution generation increase. The use of petri nets augments the ability to understand interaction between different failure modes and provides the ability to access the environmental impacts caused by combinations of the failure modes.

- Adopt the third phase of the proposed conceptual approach in evaluating technology options and process concepts, selecting the right policy for sustainable industrial development, choosing environmentally conscious techniques or whatever systems with the purpose of achieving sustainability.
- For the sake of computational efficiency and ease of data acquisition for decision makers, triangular and trapezoidal membership functions can be used to represent the defined tables of membership functions for primary and composite linguistic terms. However, the ranking method might also change.
- Application of the developed framework into other industrial-based case studies to further explore its robustness and applicability, in addition to conducting streamlined QFD, LCA and LCC studies.

To end with, the developed conceptual methodology provides a systematic and flexible approach for a manufacturing company to address the strategy for company’s competitive advantage as well as to meet the current concern for sustainability by choosing first which optimal sustainable product system improvement concept should be adopted to manufacture products that meet customer’s quality requirements, cost less and are environmentally sound.

11 SUMMARY

Worldwide competition in today’s global economies has brought significant challenges to any company that wants to meet continuously changing specific requirements of actual and potential customers and other stakeholders. Manufacturing firms that want to remain strategically competitive in the market have to address the critical issues such as protecting the environment, decreasing product cycle time, maintaining high quality, and lowering costs.

Before, industrial firms have developed products with consideration to quality requirements of customers other than price. But now, environmental concern is increasingly important within industries and government organisations. It is then paramount that environmental aspect has to be taken into account in the product development process if the existing firms want to remain competitive while meeting the current concern for sustainability in this decade. The issue of sustainability has become vital because of the report from the World Commission on Environment and Development, which focuses on the need for sustainable development as a strategy for further economic development in developed and developing countries. In addition, prevention of quality defects and environmental emissions at the source might be better than implementing solutions at the “end of a pipe”.

Firms should thereby respond to the above challenge by considering simultaneously quality, environmental and economic parameters into their product development process to maintain their competitive position. Many researchers claimed that at least 66% of the total costs of product development, manufacturing and use are determined and committed at the initial design stage prior to production, although only 5 to 10% of this entire cost is actually spent at this stage. Commonly, in spite of little and ambiguous data at the early stage, decisions are made regarding the type of resources and manufacturing processes to be used. These decisions eventually determine the nature of waste streams, the types of pollutants emitted and energy consumed during manufacture and use of the product. Nevertheless, this added environmental dimension leads to increasingly difficult job, if not challenging, to most industrial firms.

Given the above rationale, the research question of this work is focused on how manufacturing companies can be assisted in their design of products so that quality, cost and environmental requirements of the stakeholders in the life cycle phases of the product system are addressed at an early stage for the crucial purpose of maintaining a firm’s competitive advantage and meeting the current concern for sustainability. It is assumed here that industrial firm wants to have environmentally sound, consistently high quality and minimal cost products. The consideration of these three critical design aspects leads to multi-attribute decision situation with regard to the selection of optimal product system improvement concept to be pursued.

The main objective of this work is to develop a flexible decision-oriented life cycle approach that attempts to integrate cost and quality factors together with environmental parameters in the presence of imprecision and incompleteness of design data at an early stage of product development. The sub-objectives are to: (1) identify the environmental, quality and cost requirements of a reference product system; (2) determine at which stage of the life cycle phases critical emissions and high costs ensue and which product components maximise the satisfaction of the customers' quality requirements; (3) enumerate potential alternatives for system improvements to meet company's overall strategy for sustainability and assess the capability of each option for improvement to meet each strategic requirement; (4) tackle the ambiguity of design data, information and cost estimates confronted at the early product design stage; (5) apply the developed conceptual approach for choosing the most sustainable and optimal product concept for the improvement of light fitting system; and (6) confirm statistically and sensitively the ranking results obtained.

Quality function deployment (QFD) is a proven method for analysing customer's quality requirements systematically in the early stage of product development. The disadvantage of QFD is that it does not account environmental considerations. Basically, its concept is to translate the requirements of the stakeholders into product design or engineering characteristics, and then to process specifications and eventually to production requirements. Life cycle assessment (LCA), on the other hand, is also a proven method for analysing environmental performance of product in its life cycle and systems perspective. Conceptually, it is a thought process that guides the selection of options for environmental design and improvement. One of its limitations is that it does not account for non-environmental aspects such as product quality and cost. Life cycle costing (LCC) is a well-established tool for evaluating costs associated with the product system as applied to a defined life cycle as in LCA. This method provides information on which processes or components that are costly to the consumers and manufacturers. Owing to imprecise and incomplete information used for LCA, QFD and LCC at an early design stage e.g. estimated costs and emissions, it is difficult to assess with certainty the importance of the requirements, relationships between requirements and the options for system for improvements and so on. Accordingly, a fuzzy linguistic approach is proposed here because it allows one to get started with little and inexact information, and handles linguistic variables in a mathematically well-defined way.

From those 4 mentioned methodologies, a conceptual approach was developed which is made up of four major phases. Phase I involves the identification and documentation of quality, environmental and cost requirements' information through the use of modified and streamlined QFD, LCA, and LCC methods. Phase II includes the generation of alternative concepts for product system improvement using brainstorming technique and the construction of a sustainable concept comparison house or matrix where the capability of each of the options for improvement to meet the critical requirements and the importance of requirements provided by decision makers or designers were expressed in terms of fuzzy linguistic values. In Phase III, a fuzzy linguistic decision support system, which employs a fuzzy linguistic based heuristic algorithm, was developed and used to aid in the selection of the optimal sustainable product improvement concept. In Phase IV, sensitivity and statistical analyses were conducted to substantiate the preference or ranking of alternatives obtained. The primary output of this work is the developed conceptual methodology itself. This developed approach is then applied in a case study: the sustainable improvement of 2 X 10 watts splash proof universal light fitting system for office applications. There are 6 identified possible options for improvement and 17 environmental, quality and cost requirements considered.

Specific to the case study's results, the main environmental problems based on the life cycle analysis of light fitting system are global warming which is due to CO_2, toxic effects from polyaromatic hydrocarbons, consumption of fossil fuels and acidification due to SO_2 and NO_x. The major environmental emissions were found to be related to consumers' use and production of electrical energy from fossil fuels. With respect to individual components of light fitting system, the manufacture of aluminium reflector, reactor, and aluzinc-main body contributed mainly to the major environmental loads. Additionally, the critical customers' quality requirements for light fittings are its ability to withstand a humid environment, low purchasing price, simple and functional design, and even luminance without an unpleasant glare. The LCC of the reference light fitting system revealed that during the first year, the purchasing costs of the light fittings made up over 90% of the total costs. Nonetheless, over a 20-year period the energy cost could make up the largest share of the total costs, followed by the cost of light tubes and then by the cost of light fittings.

Moreover, about the result of evaluation and selection of options for product system improvement using the fuzzy linguistic decision support system, assessments based on environmental consideration, customer's product quality consideration, economic consideration, and their interrelationships were performed. When the company focuses its product improvement to environmental aspects only, then using energy conserving equipments connected to the armature, e.g., addition of modern electronic reactor, daylight switch or infrared switch, is the most suitable choice. With consideration only to customer's product quality requirements, the best alternatives are introduction of a system for recovery and post-consumption recycling of materials, use of energy conserving equipment connected to the armature, and development of new product with lower material consumption. With regard to cost aspect alone, the best choice is to change to higher wattage armature systems. With consideration to environmental and product quality requirements, the optimal options are the introduction of system for recovery and post-consumption recycling, the use of energy conserving equipment connected to the armature, and the development of new product with lower material consumption. With respect to the synergy between environmental and cost aspects, the development of a new product with lower material consumption is the most appropriate choice. With reference to product quality and cost requirements, the option that suggests the development of new product with lower material consumption is the most favourable alternative. Lastly, when one considers quality, environment and cost metrics simultaneously, then the development of a new product with lower material consumption is the optimal sustainable option to pursue.

To conclude, the contributions of this study include: (1) it attempts to integrate quality, environmental and cost requirements in the presence of imprecision and inadequacy of design data inputs at an early stage of product improvement; (2) it provides companies a life cycle approach that is holistic and preventive for design of product systems, (3) it develops a sustainable concept comparison house or matrix and a fuzzy linguistic decision heuristic algorithm to evaluate the alternatives for sustainable product improvement or development; (4) it developed specific green matrix and quality matrix; and (5) checks the robustness of the ranking proposed by the fuzzy linguistic decision algorithm.

Appendix A Selected Methods for Composition of Two Fuzzy Relations

(Source: Kaufmann, 1975, pp. 60-65)

1. Max-min composition.

Let $\tilde{\mathfrak{R}}_1 \subset X \times Y$ and $\tilde{\mathfrak{R}}_2 \subset Y \times Z$. Let's define the max-min composition of $\tilde{\mathfrak{R}}_1$ and $\tilde{\mathfrak{R}}_2$, denoted $\tilde{\mathfrak{R}}_2 \circ \tilde{\mathfrak{R}}_1$, by the expression

$$\mu_{\tilde{\mathfrak{R}}_2 \circ \tilde{\mathfrak{R}}_1}(x,z) = \underset{y}{\vee}\left[\mu_{\tilde{\mathfrak{R}}_1}(x,y) \wedge \mu_{\tilde{\mathfrak{R}}_2}(y,z)\right] \qquad (1)$$

$$= \underset{y}{MAX}\left[MIN\left(\mu_{\tilde{\mathfrak{R}}_1}(x,y), \mu_{\tilde{\mathfrak{R}}_2}(y,z\right)\right], \qquad (2)$$

where $x \in X, y \in Y,$ *and* $z \in Z.$

Example: Consider two fuzzy relations $x\tilde{\mathfrak{R}}_1 y$ *and* $y\tilde{\mathfrak{R}}_2 z$, where x, y and z∈ R^+. Suppose that

$\tilde{\mathfrak{R}}_1$

	Y_1	Y_2	Y_3	Y_4	Y_5
X_1	0.1	0.2	0.0	1.0	0.7
X_2	0.3	0.5	0.0	0,2	1.0
X_3	0.8	0.0	1.0	0.4	0.3

(a)

$\tilde{\mathfrak{R}}_2$

	Z_1	Z_2	Z_3	Z_4
Y_1	0.9	0.0	0.3	0.4
Y_2	0.2	1.0	0.8	0.0
Y_3	0.8	0.0	0.7	1.0
Y_4	0.4	0.2	0.3	0.0
Y_5	0.0	1.0	0.0	0.8

(b)

$\tilde{\mathfrak{R}}_2 \circ \tilde{\mathfrak{R}}_1$

	Z_1	Z_2	Z_3	Z_4
X_1	0.4	0.7	0.3	0.7
X_2	0.3	1.0	0.5	0.8
X_3	0.8	0.3	0.7	1.0

(c)

Calculation for the above tables is shown below.

$(x,z) = (x_1, z_1)$

$$MIN\left(\mu_{\tilde{\mathfrak{R}}_1}(x_1,y_1), \mu_{\tilde{\mathfrak{R}}_2}(y_1,z_1)\right) \qquad (3)$$

$$= MIN(0.1, 0.9)$$

$$= 0.1$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_2),\mu_{\tilde{\Re}_2}(y_2,z_1)\right) \qquad (4)$$
$$=MIN(0.2,0.2)$$
$$=0.2$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_3),\mu_{\tilde{\Re}_2}(y_3,z_1)\right) \qquad (5)$$
$$=MIN(0.0,0.8)$$
$$=0.0$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_4),\mu_{\tilde{\Re}_2}(y_4,z_1)\right) \qquad (6)$$
$$=MIN(1.0,0.4)$$
$$=0.4$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_5),\mu_{\tilde{\Re}_2}(y_5,z_1)\right) \qquad (7)$$
$$=MIN(0.7,0.0)$$
$$=0.0$$

$$\underset{y_i}{MAX}\left[MIN\left((\mu_{\tilde{\Re}_1}(x_1,y_i),\mu_{\tilde{\Re}_2}(y_i,z_1)\right)\right] \qquad (8)$$
$$=MAX(0.1,0.2,0.0,0.4,0)$$
$$=0.4$$

Now let

$$(x,z)=(x_1,z_2) \qquad (9)$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_1),\mu_{\tilde{\Re}_2}(y_1,z_2)\right) \qquad (10)$$
$$=MIN(0.1,0.0)$$
$$=0.0$$

$$MIN\left(\mu_{\tilde{\Re}_1}(x_1,y_2),\mu_{\tilde{\Re}_2}(y_2,z_2)\right) \qquad (11)$$
$$=MIN(0.2,1.0)$$
$$=0.2,\ldots\ldots$$

and so on. The results are given in Table (c) in the previous page.

2. Max-star composition.

This composition operation is similar to max-min method but differs on the replacement of $\wedge$ with a star * which is also associative and monotone nondecreasing in each argument. One may write the function such as shown in equation (12).

$$\mu_{\tilde{\mathfrak{I}} * \tilde{\mathfrak{R}}}(x,z) = \bigvee_{y}\left[\mu_{\tilde{\mathfrak{R}}}(x,y) * \mu_{\tilde{\mathfrak{I}}}(y,z)\right] \qquad (12)$$

3. Max-product composition.

Among the max-star compositions that may be imagined, the max-product composition deserves attention. In this case the operation $*$ will be the product designated by a period (**.**), then the formula in the preceding equation (12) becomes

$$\mu_{\tilde{\mathfrak{I}} \cdot \tilde{\mathfrak{R}}}(x,z) = \bigvee_{y}\left[\mu_{\tilde{\mathfrak{R}}}(x,y) \cdot \mu_{\tilde{\mathfrak{I}}}(y,z)\right] \qquad (13)$$

Appendix B Computer Softwares for LCA

Software, Language & Operating System	***Comments***
Boustead-model English MS-DOS	Model contains data on energy and over 2000 processes. For LC studies of e.g. packaging.
Eko Tool English MS-DOS	Not pure LCA-software. For optimising of linear models. Treats environmental issues as costs
EPS 2.0 (Environmental Priority Strategies) English Windows Excel	For evaluation of inventory results. EPS-, ecological scarcity and environmental themes methods available. Sensitivity and error analysis features.
Gabi-Basis German & English Windows	For inventory. Data come mainly from partner companies and cover energy, transport, emissions, and waste management. Plans exist for yearly update and inclusion of evaluation elements
IDEA (International Database for Ecoprofile Analysis) English DBase IV	For detailed inventory and analysis of large systems. Contains an extensive database on basic materials, energy conversion, production and transport.
KCL-ECO English Macintosh	For inventory. Designed mainly for process industry. Data come from industry, focusing on chemical forest industry. Flexible use and graphical interface. Commercially available.
LCA Inventory Tool (LCAit) English Windows	For inventory. Graphical process tree. Data for materials, transportation and energy carriers. Ready-made LCAs and additional data sets available. Supports dynamic data exchange (DDE).
Öko-Base II German MS-DOS	Database for analysing and selecting packaging and products. Based on the BUWAL method and data. Developed for Swiss circumstances.
Öko-Pack German MS-DOS	For inventory of packaging. Based on the BUWAL-reports 132 &133.
PEMS.1 (PIRA Environmental Management System) English Windows Excel	For inventory of general products. A regularly updated industrial database. Evaluation aspects are being developed.
PIA (Product Improvement Analysis) Dutch and English MS-DOS	For inventory. Data on energy production, transportation and waste treatment. Inclusion of financial module is being considered.
PLA Educational Tool English Windows	For presentation and evaluation of inventory results. Utilises graphical presentation, so called LifeWay.

Procter & Gamble English Windows Excel/Lotus	For inventory of packaging. Data obtained from BUWAL-report 132.
SimaPro2 English MS-DOS	Designer’s tool to quickly assess the environmental effects of a product or material. Contains a database of several basic materials and processes. Contains also result analysis option
Sundström-model	Miljöbalans does life cycle studies for general products. The approach is defined for each client individually.
TEMIS (Total Emission Model for Integrated Systems) German & English MS-DOS	Mainly for analysing different energy systems. Can also be used for analysing transportation systems and material process chains. Database covers the standard energy systems
TEA (Tools for Ecological Analysis) Windows	For inventory of complex products. Database on the main materials used in industry. Cost module helps to understand financial consequences of different systems.

Source: Weidema, 1993, p. 94-95

Appendix C Available Software Tools for QFD

QFD Tools	Description
QFD/Capture 3.2 (standard edition) (Professional edition)	Input and output formats in HTML format Automatically generated customer questionnaire, also in HTML format Use of HTML functionalities for documentation Developed in Germany
Decision/Capture ™	Tool for supporting decisions
QFD Guide	Beginner's Tool for QFD/Capture
QFD Designer 3.15	Identical to QFD Designer QS of ASI Developed in USA
Qualica QFD Version 1.6 & 2.0	With Excel interface Matrix data analysis Pair comparison
CIMOS QFD Software	QFD software under DOS with large functionality and CAD Interface Windows-based and interface with CIMOS FMEA software
QFD designer QA	Identical with QFD Designer of Qualisoft Developed in USA
QFD Work	Developed in UK
QFD 2000	The following tools are included: QFD flow, Affinity Diagram, Tree Diagram, Customer Voice, Questionnaire, Analysis of Customer, Graphical Analysis, FMEA analysis and etc. Developed in UK
QFDT	Developed in Japan
QFD	Developed in Yugoslavia
QFD Scope	Windows-based QFD tool with QFD design tool, QFD Affinity Diagram, QFD Tree and QFD multiple matrix Developed in USA

Source: QFD Institute of Cologne (http://www.qfd-id.de)

Appendix D Idea Generation Techniques

(Source: Reader, 1996, 258-259)

Method	***Characteristics***	***Objectives***
Abstraction (progressive abstraction)	Make problem or situation more abstract	Insights into new solutions
Adaptation	Modifying for partial transformation of an existing product for different conditions	Reliable solution for new conditions
Aggregation	Combination of product characteristics into a single product or of functions of a number of products into one product	New properties, simplified structure
Analysis of properties (attribute listing)	Thorough analysis of every property of the product	Improvement of an existing product
Application	Application of an existing product for new functions	Application of a proven product to new areas of use
Attribute-based discriminant analysis (PREFMAP)	Market segments developed on basis of brand preferences, geometric representation developed by discriminant analysis from brand's effective attributes, then mapped and analysed	Market structure generated and searched for new product opportunities
Brainstorming	Collect ideas in freewheeling discussion without criticism	Find many new ideas
Combinations with interactions	Combining of a product or of properties to obtain new and more complicated effects	Derive new solutions from existing products
Critical Path Network	Graphic representation of activities and their duration	Create an overview of the sequence and timing and find the critical path to identify opportunities
Descartes	Four principles: criticism, division, ordering, create overview	Correctness and effectiveness of thought process stimulates ideas
Dimensional investigation	Technical and economic properties of the product brought together into a mathematical relationship and extreme values found	Find optimal solution on product properties
Division of totality	Tactical procedure based on the division of a while concept or problem into component parts	Create overview, generate partial solutions

Evaluation	Find technical and economic valuation by point counting	Find best variant among a few
Experimentation	By measuring and testing, obtain desired values	Determination of product
Incubation	After thorough preparation of the problem, take a break	Find ideas by intuition
Iteration	Starting from assumed values, obtain progressively closer approximation of all values	Solution of a system with complicated interactions
Market research	Systematic collection and classification of market information	Establishing market conditions and opportunities
Mental experiment	Observe an idealised mental model at work	Testing of an idea, determination of behaviour
Methodical doubt (scientific scepticism)	By systematic negation of existing solution, search for new solution paths	Find new solutions, opportunities
Method ‘6-3-5’	6 participants; each writes down 3 ideas within 5 minutes, passing ideas on to the next person for 3 similar ideas, working all the way around the group	Find many solutions, ideas
Morphological analysis/matrix	Split up problem into parts and look for partial solutions to each, leading to generation of solutions to original problem	New solutions by combinations of functions
Problem inventory analysis (reverse brainstorming)	Expand problem, reformulate by stating objective in standard format	Look for new solutions
Questioning	By applying a system of questions, find gapless information or produce mental stimulation	Obtain most complete information possible
Step forwards/backwards	Attempt both solution directions from ‘is’ to ‘should be’ and reverse	Find most favourable path to a solution
Synetics	Team analyses problem and searches for new solutions through analysis	Discover new solutions, opportunities
Systematic search of field	Research all directions starting from fixed points of the region	Obtain most complete information possible
Systems approach	Systematic working in every situation requiring a solution or decision	As far as possible complete investigation

Techno economic design	By technical and economic evaluation find and improve the strong features of the product	Improve product
Technological environmental forecasting	Develop broad scenarios about the future in general, then technology in particular	Insight into the future
Value analysis or engineering	Analysis and criticism of the existing solution from the economic viewpoint	Improve economic properties of the product

Appendix E Summary of Life Cycle Inventory Data of 12 Light Fitting Systems

		Life Cycle Stages									
Materials/ Energy	Unit	Aluzinc Main Body	Reflector	Acrylic Diffuser	ABS endcaps	Reactor	Packaging	Production and Assembly	Light Tubes	Use	Total Amount
Aluminium	kg	0.17	2.88	-	-	-	-	-	-	-	3.05
Zinc	kg	0.12	-	-	-		-	-		-	0.12
Steel		15.994	-	-	-	8.00	-	-	-	-	23.994
PMMA granules	kg	-	-	6.96	-	-	-	-	-	-	6.96
Copper	kg	-	-	-	-	1.12	-	-	-	-	1.12
ABS granules		-	-	-	2.28	-	-	-	-	-	2.28
Cardboard	kg	-	-	-	-	-	2.88	-	-	-	2.88
Electricity	MJ	-	-	-	-	-	-	-	-	11200	11200
Fossil Fuels	MJ	100	200	100	100	200	25	500	25	-	12350
Emissions/ Effluents											
CO2	kg	20	15	15	10	15	2	15	495	1200	1864
SO2	g	80	50	80	35	42	5	20	5	4400	4600
NOx	g	45	20	95	40	42	15	15	13	3470	3700
HC/ NMVOC	g	10	15	95	30	10	5	50	3	260	455
PAH	g	3.06	0	0	0	3.06	0	0	0	0	6.12

Notes: **-** denotes “not applicable”; kg means kilograms; MJ signifies Megajoules

Appendix F Diagrams of Membership Functions Used

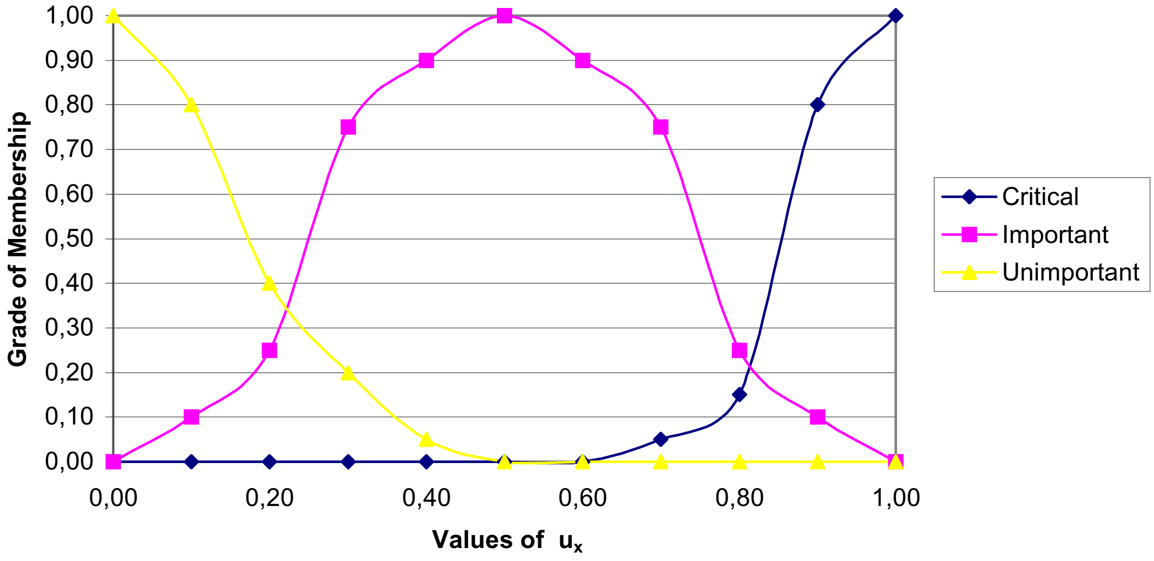


Diagram of Membership Functions of Primary Linguistic Values of “X= Importance”

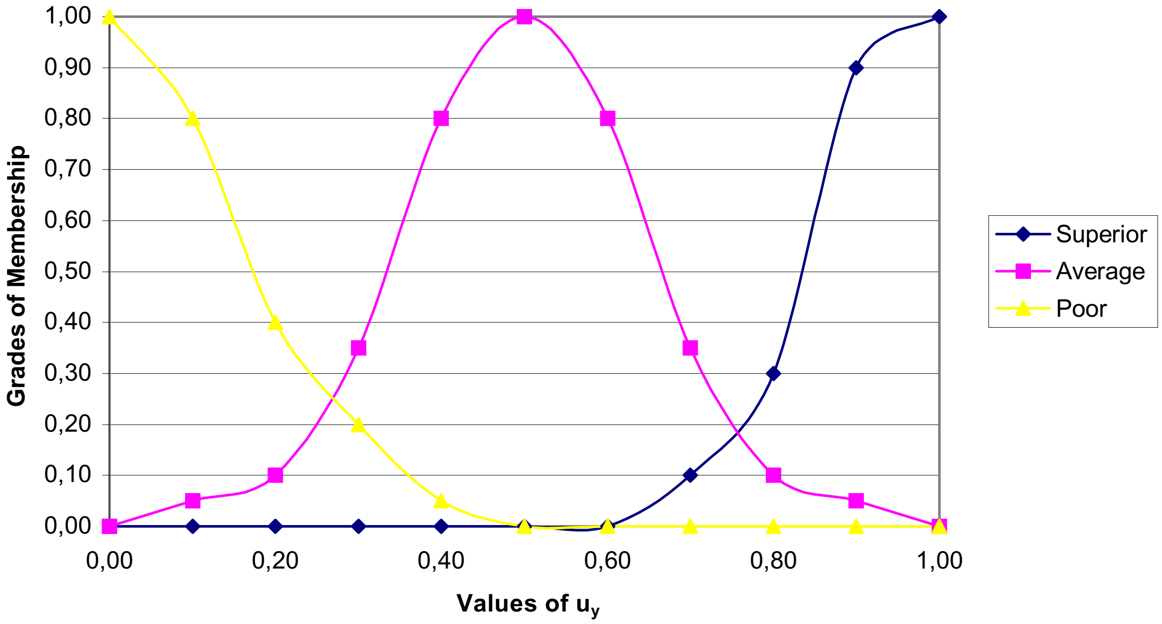


Diagram of Membership Functions of Primary Linguistic Values of “Y=Capability”

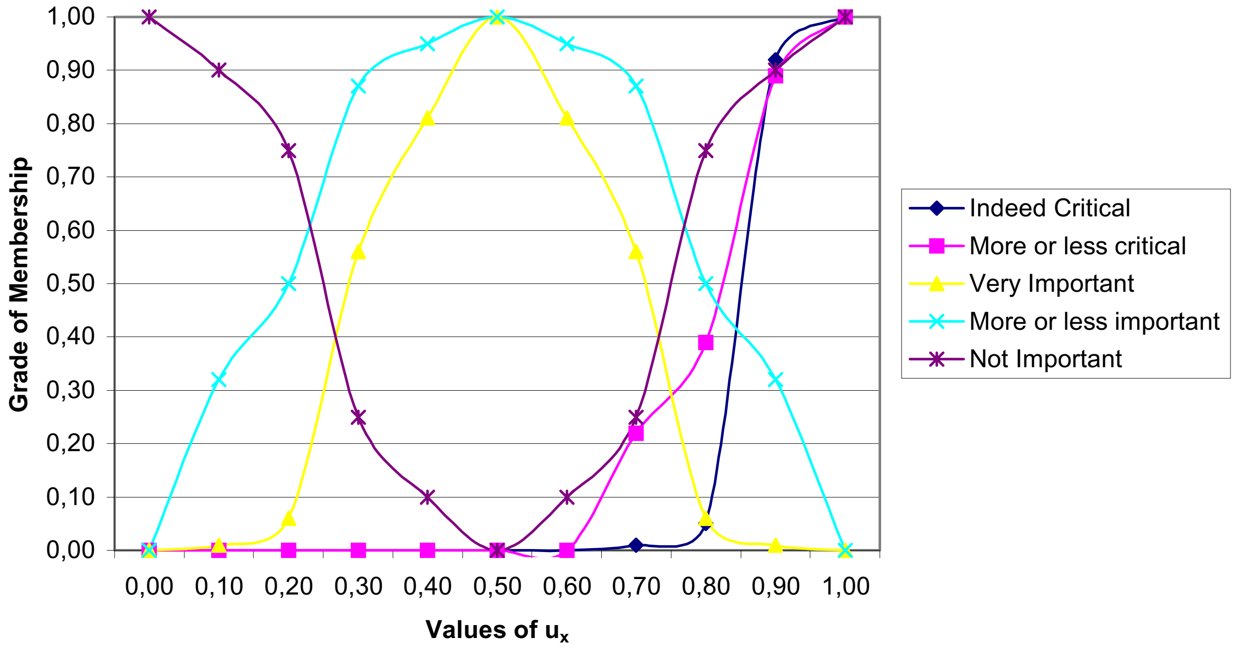


Diagram of Membership Functions for Composite Linguistic Values of " X= Importance"

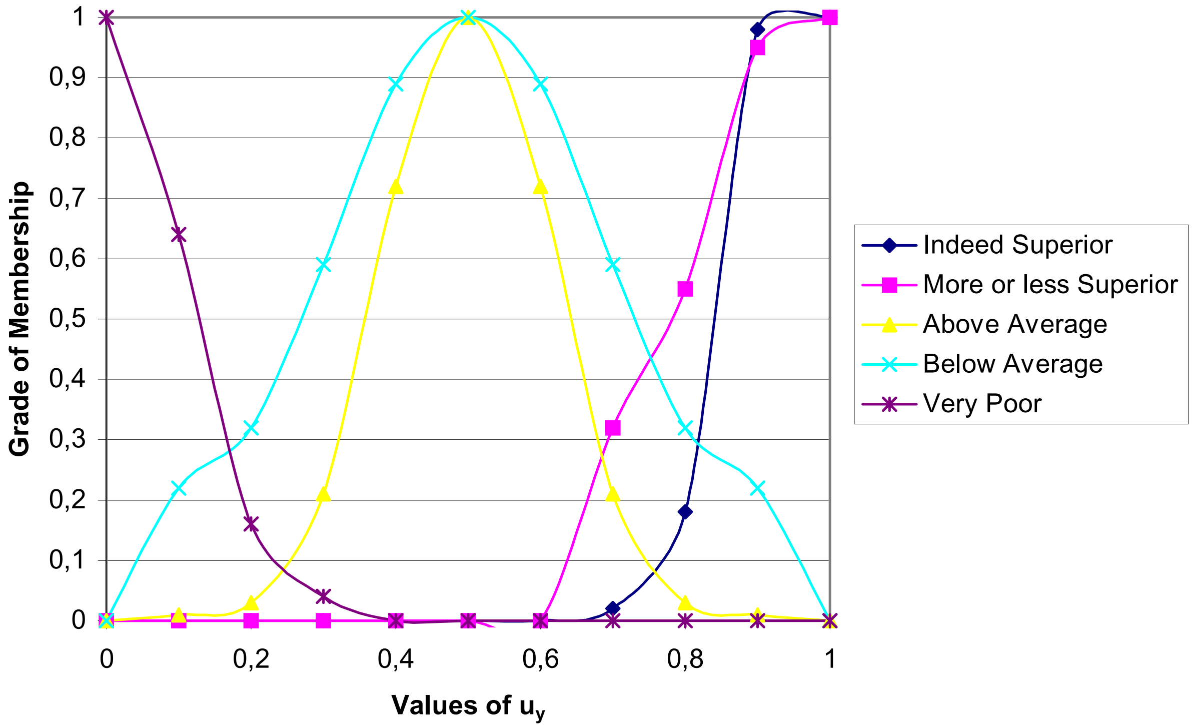


Diagram of Membership Functions for Composite Linguistic Values of "Y= Capability"

Appendix G Four Main Categories for Product System Improvements

What to Improve in Product Systems?

I. Redefinition of user needs and requirements
- Modify the requirements of customers
- Change the weighting of customer requirements
- Find new solutions outside the scope of current situation
- Redefine system boundaries to find new solution outside the system

II. Improvement of product performance
- Increase the efficiency in fulfilling user needs and requirements
- Increase the total life span of the product by making it more durable and easier to repair
- Increase flexibility in design of product so that parts of the product can be upgraded without changing the whole product
- Design for cascade functions (primary, secondary and tertiary functions)
- Make the product more compact to reduce weight and material consumption

III. Substitution/elimination of components of the product system
- Replace the whole product concept
- Substitute/eliminate one main component (e.g. raw material)
- Substitute/eliminate one unit of the product system

IV. Optimisation within the system units and within networks of system units
- Waste minimisation
- Change from waste to by-product
- On-site recycling
- Off-site recovery
- Optimisation of transport and logistics

Source: Hanssen, 1997

Appendix H Impact Assessment Factors of Emissions and Consumptions Used According to Impact Category

Substance/Energy	Impact Category	Impact Assessment Factor
CO2	Global Warming	1 kg CO2-equ./kg
SO2	Acidification Potential	0.1095 kg SO2-equ/kg.
	Humantoxicity	2.50 X 10^{7}m3Air/kg
	Ecotoxicity of Air	2.50 X 107 m3 Air/kg
NOx	Acidification Potential	0.70 kg. SO2 equivalent/kg
	Nutrification Potential	0.13 kg PO43-equivalent7kg
	Human Toxicity	2.00 X 107 m3 Air/kg
	Ecotoxicity of Air	2.00 X 107 m3Air/kg
NMVOC	Photochemical Oxidant Formation	0.416 kg ether equivalent/kg.
PAH	Impairment of Maritime Environment	0.5 (non-dimensional)
Fossil Fuels	Conversion of Fossil Fuels	0.4364 (non-dimensional)

Source : Rentz et al., 1998

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LEBENSLAUF

Persönliche Daten

Name	Anthony Basco Halog
Anschrift	Blk. 6, Lot. 10, Vista Verde Subdivision Diversion Road, Panacan Davao City, 8000, Philippinen
Geburtsdatum, Geburtsort	28.04.1968, Davao City/Philippinen
Familienstand	verheiratet, eine Tochter
Staatsangehörigkeit:	philippinisch

Schulbildung

Juni 1974 – March 1975	Kindergarten Rotary Kindergarten School Davao City, Philippinen
Juni 1975 – March 1981	Elementary Education Balagtas Elementary School Davao City, Philippinen
Juni 1981 – March 1985	Secondary Education Davao City High School, Davao City, Philippinen

Studium

Juni 1985 – March 1990	Bachelor of Science in Chemical Engineering (Magna Cum laude) University of Mindanao, Davao City, Philippinen

May 1992 – December 1993	Master of Engineering (With Very Good Thesis) (Industrial Engineering and Management) Asian Institute of Technology, Bangkok, Thailand
July1996- July 1998	Master of Business Administration (MBA) (With Distinction) Monash University, Melbourne, Australia

Beruflicher Werdegang

01.04.1999 – 16.03.2002	Doktorand/Stipendiat des DAAD am Institut für Industriebetriebslehre und Industrielle Produktion (IIP) der Universität Karlsruhe (TH)
01.06.1995 – 01.06.1996	Assistant Professor, Department of Industrial Engineering De La Salle University Manila, Philippinen
16.03.1996 – 20.06.1996	ISO 9000 Consultant Purefoods Corporation Marikina, Philippinen
01.06.1994 – 31.05.1995	Quality Manager/ISO 9000 Representative ACEL Precision Plastics Pte. Ltd. Singapore
01.01.1994 – 15.05.1994	Quality Assurance Supervisor Dynamic Group of Companies Bangkok, Thailand
01.10.1990 – 30.04.1992	Quality Assurance Analyst Purefoods Corporation, Marikina, Philippinen