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INTELLIGENT DESIGN OF ENVIRONMENTAL PERFORMANCE EVALUATION FOR SUSTAINABLE-PRODUCT DEVELOPMENT

by

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This work is dedicated to

My husband Wahyu Widyatmaka

My Children Widyasari Puspa Permata Witra and Widyakresna Soekarno Permana Witra

My parents H.M. Soekarno and Hj. Sri Wuryani

For their love, support and encouragement



Abstract

Due to the increasing demand for green manufacturing and environmentally friendly products environmental performance evaluation (EPE) is now a necessity for manufacturing companies. Environmental performance evaluation is an internal process of any manufacturing organisation through which they can identify their environmental indicators (such as energy consumption, solid waste and reprocessed materials) with highest negative impact on the environment. Environmental performance evaluation is, in fact, an approach to Design for Environment, hence ideally it should be integrated with the Product Design activities to lead to green products; this is lacking in the current environmental performance evaluation methods.

To fill this gap an intelligent environmental performance evaluation model was developed herein. The model is used at the design stage of products, as a tool for Design for Environment. It can accommodate different environmental indicators as input, produces the environmental performance in linguistic terms (e.g. moderate, satistisfied, and optimum) as output. This helps the company continuously monitor their environmental impacts via controlling their environmental indicators.

This new environmental performance evaluation model is designed using design for six sigma (DFSS) with IDOV activities (*identify*, *design*, *optimise* and *validate*). The model consists of two main parts namely the quantitative presentation of fuzzy quality function deployment (fuzzy QFD) with environmental concern, and application of fuzzy inference system (FIS) integrated with Taguchi method. The quantitative presentation of fuzzy QFD takes care of the environmental requirements, environmental indicators and then prioritising them to be used as input variables to the model. Environmental performance as a function of environmental indicators is evaluated via fuzzification of a transfer algorithm by applying FIS integrated with Taguchi method. Taguchi method is performed to analyse the main contribution of environmental indicators to the environmental performance.

The environmental data from a textile manufacturing industry in Indonesia was conducted to validate the developed model. The case study demonstrated the applicability and usefulness of the model in helping the company continuously monitor and improve their negative environmental impacts.

Declaration

I declare that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university or institution. To the best of my knowledge it does not contain any material previously published or written by another person, except where due reference is made.

Pregiwati Pusporini

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List of Abbreviations

AHP	Analytical hierarchy process
ANOVA	Analysis of variance
BOD	Biochemical oxygen demand
BSC	Balanced scorecard
C	Manufacturing cost
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COPQ	Cost of poor quality
CR	Customer requirements
CTQ	Critical to quality
CUSUM	The cumulative sum
CV	Contingent valuation
D	Product defect
DEA	Data envelopment analysis
DfE	Design for environment
DFSS	Design for six-sigma
DMADV	Define, measure, analyse, design, verify
DMAIC	Define, measure, analyse, improve, control
DPMO	Defect per million opportunities
E	Energy consumption
ECI	Environmental condition indicators
Eco-QFD	Eco-quality function deployment
EI	Environmental indicators
EM	Engineering metric
EMI	Environmental management indicators
EMS	Environmental management system
EP	Environmental performance
EPA	Environmental performance assessment
EPE	Environmental performance evaluation
EPI	Environmental performance indicators
ER	Environmental requirements

F-ANP	Fuzzy-analytic network process
FIS	Fuzzy inference system
FMEA	Failure mode effect analysis
F-PROMETHEE	Fuzzy-preference ranking organisation method for enrichment evaluations
GDP	Gross domestic product
GQFD	Green quality function deployment
GQH	Green quality house
GWP	Global warming potential
HOE	House of ecology
HOQ	House of quality
IDOV	Identify, design, optimise, validate
KPIs	Key performance indicators
KPIVs	Key performance input variables
LCA	Life cycle assessment
LCC	Life cycle cost
LCP	Life cycle planning
LF	Labour force
LTB	Larger the better
M	Market share
MCDM	Multi criteria decision making
MP	Matrix of parts
MPI	Management performance indicators
MSA	Multi criteria analysis
MTBF	Mean time between failures
MTTF	Mean time to failure
NO_x	Nitrogen oxides
NTB	Nominal the best
OD	Ozone depletion
OEE	Overall equipment effectiveness
OPI	Operational performance indicators
PEC	Primary energy consumption
PEPA	Process environmental performance assessment
PO	Photochemical oxidation
PTR	Product technical requirements
QFD	Quality function deployment

QFDE	Quality function deployment for environment
QM	Quality management
R	Reliability
R	Reprocessed materials
S	Solid waste
SEM	Structural equation modelling
SMEs	Small medium enterprises
SO_2	Sulphur oxides
STB	Smaller the better
TFNs	Triangular fuzzy numbers
TOC	Total organic carbon
TOPSIS	The technique for order of preference by similarity to ideal solution
TPH	Total petroleum hydrocarbons
TRIZ	Theory of inventive problem solving
VOC	Voice of customer
W	Wastewater treatment system
WIP	Work in process
WTP	Willingness to pay

List of Publications

Journal Papers

Pusporini, P., K. Abhary, and L. Luong, *Environmental performance as key performance indicators in the lean six-sigma methodology.* Advanced Materials Research, 2012. **488-489**: p. 1082-1086.

Pusporini, P., K. Abhary, and L. Luong, *Integrating environmental requirements into quality function deployment for designing eco-friendly product.* International Journal of Materials, Mechanics and Manufacturing, 2013. **1(1)**: p. 80-84.

Pusporini, P., K. Abhary, and L. Luong, *Development of environmental performance model using design for six sigma (DFSS).* International Journal of Materials, Mechanics and Manufacturing, 2013. **1(1)**: p. 102-106.

Pusporini, P., K. Abhary, and L. Luong, *Intelligent design of environmental performance evaluation using fuzzy expert system.* Applied Mechanics and Materials, 2013. **330**: p. 719-723.

Conference Papers

Pusporini, P., K. Abhary, and L. Luong. *Introducing environmental aspects into lean six sigma concept for sustainable product development: A literature survey*. in *The 12th International Conference on QiR (Quality in Research)*. 4-7 July 2011. Bali, Indonesia.

Pusporini, P., K. Abhary, and L. Luong. Integration of fuzzy inference system and Taguchi's experiments to design a model of environmental performance evaluation. In *The IEEE Symposium on Business, Engineering and Industrial Applications (ISBEIA)*. 22-25 September 2013. Kuching, Malaysia.

Chapter One

Background and Research Scope



1.1 Introduction

This chapter describes the research background of this thesis and aims at demonstrating the importance of an eco-design concept in dealing with environmental consideration as a major attention for sustainable product development. Environmental evaluation is described herein as an important part of product design and development processes with the main problems highlighted. The scope of the research will be presented followed by the motivation and finally the organisation of the thesis is introduced.

1.2 The importance of an eco-design concept for sustainable product development

In the last decades many organisations and companies all over the world have become aware of the fact that they should reduce the environmental impact of their business activities. This implies that companies need to consider both economic and ecological aspects simultaneously related to sustainable product development.

Sustainable development in the product development concept refers to a dynamic process that harmonises economic activities with ecological processes. Sustainable product development will focus on environmental optimisation of products and processes, aiming to create product designs that are ecologically sustainable while providing functions that meet basic human needs. To achieve sustainable product development there is a need to integrate environmental issues into the product development process that meet many other demands such as global competitiveness, shortened development cycles and high quality at least cost (Keoleian and Menerey 1994). It is important to systematically integrate environmental consideration into the design process throughout a product's life cycle. Environmental factors should be viewed as an attractive opportunity rather than as a threat. This recognises that preventive action is better than cure and the company has to attempt to design rather than simply manage the problems (Bhamra 2004).

In the last two decades terminology has been introduced relating to the integration of environmental considerations into the design stage such as *environmentally conscious design*, *design for environment*, *life cycle design* and *eco-design*. Even though these terminologies are quite similar they may have specific applications to represent varying degrees of environmental integration or innovation. The concept of eco-design will integrate environmental issues in the product development and related processes by

applying criteria with the main purpose of preventing waste, emission and environmental impact along the lifecycle of products (Pigosso, Rozenfeld and McAloone 2013; van Weenen 1995). This concept needs to be employed to move towards a more sustainable future as it integrates environmental issues into product development and related processes with the main aim of minimising environmental impacts throughout the product's life cycle without compromising other essential criteria such as *performance, cost, quality* and *functionality* (Bhamra 2004; Johansson 2002; van Weenen 1995).

There are two main activities related to eco-design practices namely eco-design management practices and eco-design operational practices that are interrelated. Eco-design management practices are all activities related to product development and its processes to address environmental concerns from a managerial perspective while eco-design operational practices concentrates more on the technical issues of product specification and design. Therefore, potential environmental impacts through the product's life cycle will have a greater influence on the selection of the operational practice for a particular project (Pigosso, Rozenfeld and McAloone 2013).

The management or the expert team in industry can initiate the process of integrating environmental aspects into product design and development. There are many various driving forces, both external and internal, for an organisation to implement eco-design into their business activities such as product standard, cost savings, legislative regulations, competitor information, market pressure, industrial customer requirements, innovation, employee motivation, company responsibility and communication and other stakeholders (Bhamra 2004; Kengpol and Boonkanit 2011). These factors force companies to consider eco-design as an integrated part of their product development. By conducting environmental responsibility it will lead to increased and improved manufacturer's performance including processes, products and practices such as 'waste minimisation' and 'zero emission' (Azapagic 1999). Also the implementation of design for the environment in the product development process will have a significant impact on improving environmental aspects of products and increase product competitiveness (Choi, Nies and Ramani 2008).

The main consideration of eco-design of products in a company or organisation is how to fulfil customer and environmental requirements and provide a benefit to the customer at

the lowest environmental/economic cost. The concept of environmental awareness with its aspects and impacts need to be implemented into product design development activities to properly address environmental demands (Luttropp and Lagerstedt 2006).

It is important to introduce the eco-design concept at an early phase of the product design and development process as the design process is one of the major tasks for any company. It will be responsible for two major types of design activities namely *new product design and development*, and *process design and development* (Sroufe *et al.* 2000) both of which are closely interrelated and have a significant impact on the environment. A company or organisation has to consider these activities to ensure that effective and efficient designs and processes have been properly developed and implemented. Furthermore, the product design activities which include environmental considerations will assist organisations to highlight some opportunities to solve their environmental problems as it has been recognised that a lot of waste occurs as a result of design process activities and can reach 80-90 percent of a product's environmental and economic costs (Argument, Lettice and Bhamra 1998; Mascle and Zhao 2008).

Finally, the concept of eco-design determines the design specification during the product development process and also relates to prior phases of design specification. This indicates that environmental issues should be considered at the very beginning of the product development process to achieve sustainability.

1.3 Environmental evaluation as an important part of product design and development process

Due to the growing concern of environmental problems caused by manufacturing industries, and also consumer demands for environmentally friendly products, they have been forced to increase awareness of environmental issues by improving and optimising methods and controlling their production processes to reduce environmental impacts. Humphreys *et al.* (2006) highlighted that in the last decades organisations have been addressing environmental problems by implementing such programs with the main aim to reduce emissions, waste and energy consumption. The new eco-auditing framework needs to be introduced for enterprises to improve their operating procedures to ensure they are environmental friendly.

Manufacturing industries should be proactive in creating the design of environmentally friendly products. These industries need to introduce the integration of environmental aspects into their organisation to reduce the environmental impact and to be more concerned about environmental aspects (Cristofari, Deshmukh and Wang 1996; Höjer *et al.* 2008; Sakao 2007; Shane 2003). Environmental issues also have significant implications for environmental protection and sustainable development and will lead to creating environmentally conscious design (Eco-designs) which focuses on environmental effect and resource consumption along with the product life cycle (Yongming, Luo and Li 2009). The ISO/TR 14062 highlighted the concept that integrating environmental aspects can be elaborated in all steps of product design and development processes (Lee, K-M 2002).

Moreover, increasing competitiveness amongst manufacturing industries will force them to take a lead in continuous quality improvement to create and manage their business processes more efficiently and effectively. This indicates that environmental aspects, including environmental indicators and its evaluation, are becoming an important part of product design and development processes. Every production process in the manufacturing industry will relate to the environment hence the assessment of environmental indicators is required to identify, evaluate and eliminate significant negative impact on the environment. By conducting this evaluation it is expected to reduce or eliminate the environmental impact.

The integration of environmental aspects into the product development process influences the achievement of overall competitiveness of products. Giancarlo (2005) indicated that environmental and quality performance should be integrated as a new business strategy to achieve environmental continuous improvement. Jeronimo de Burgos and Jose (2001) pointed out that environmental performance should be introduced as an operation objective. Environmental performance as part of an environmental aspect should be considered during the product design and development processes and also this performance can be set as a target for project improvement. The new paradigm of operation management which focuses on cost, quality, time, service and environmental performance has been recommended to achieve environmentally sustainable product development (Jeronimo de Burgos and Jose 2001). Kaebernick, Kara and Sun (2003) supported the paradigm that product development can create a new paradigm for

sustainable manufacturing that will introduce environmental perspectives at every stage of the product design and development processes. The environmental aspect and performance have to be integrated as part of product design and development process and considered as a target for continuous improvement effort. This evaluation has become an important measure of business in the manufacturing industry. Environmental evaluation is needed for the environmental performance to meet the target value set by the organisation's management.

The main reason for integrating environmental aspects, including environmental measurement in the product design and development process, is to reduce the environmental impact of products throughout their complete life cycle. There are many potential advantages for both customers and stakeholders to be gained by introducing environmental aspects into the business activities such as reducing the cost by optimising the use of effective materials and energy, increasing process efficiency, reducing waste and disposal, and meeting customer expectations; these improvements can lead to the eco-design or design for environment (DfE). This concept covers all design activities with the main purpose of improving environmental performance of a product (Hauschild, Jeswiet and Alting 2004). The conscious effort of product development has to involve environmental consideration among its product design and development and include environmental performance evaluation as an important part of this process. Consequently, environmental consideration in product development must be viewed as an important element of environmental concern in companies or organisations.

Growing concern in companies and organisations about environmental issues is due to the pressure from public opinion and stakeholders to improve their environmental performance. For this reason environmental indicators are becoming an important consideration at the company level. Although companies may have different circumstances and each have their own process activities and environmental goals they need to integrate green issues into their overall process to reduce environmental impacts by designing individual environmental performance for their respective company.

The current problem in environmental performance evaluation is that it is commonly carried out quite late in the product and development process and not integrated into any development activities. Integrating this evaluation into product design and development

is a hard task as the environmental indicators framework is complex. Also this evaluation will involve human judgments that are commonly subjective, vague and imprecise. Further research is required to address these issues. Figure 1.1 presents the example framework of environmental indicators.

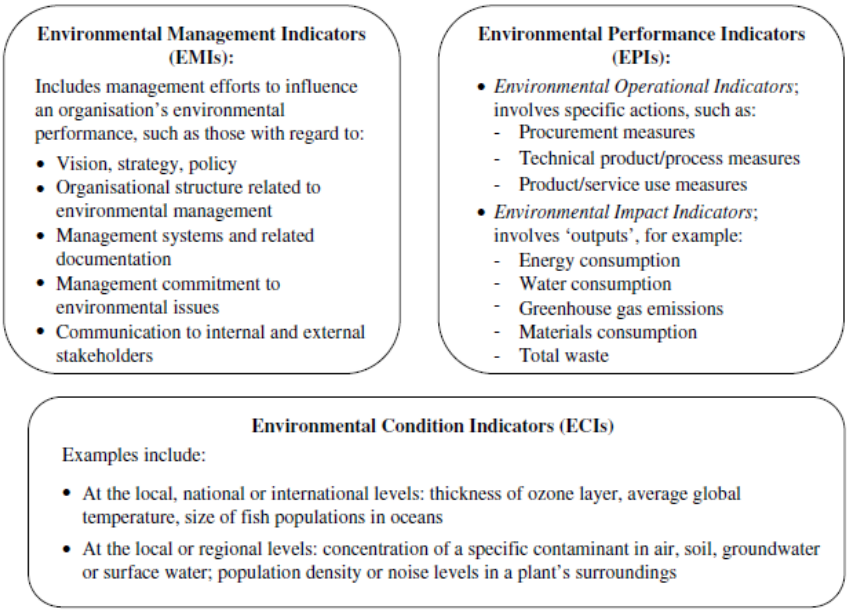


Figure 1.1 Framework of environmental indicators (Kolk and Mauser 2002)

These indicators can be from either internal or external organisations where developing an environmental performance evaluation model and optimising the evaluation process can be a challenging task, hence further research is required to integrate the environmental performance evaluation model into product design and development . This evaluation model should be able to accommodate many varying environmental indicators and possibly be incorporated into continuous improvement effort as a target for enhancing projects.

When environmental performance indicators have been developed the expert team will need to determine what measures and metrics of environmental indicators are appropriate for their particular business conditions and specific circumstances. Environmental performance evaluation should have measurable outcomes to reflect environmental improvement and support continuous improvement efforts. Research is required to understand how to identify appropriate environmental performance measures and how to design a model for environmental performance evaluation applicable to manufacturing industry so they meet their environmental requirements and business goals.

The above mentioned research gaps along with all others are explained in details in Section 2.5 and 2.7.

A comprehensive, flexible and adaptable framework for evaluating environmental performance is needed to address the lack of environmental performance measurement and accommodate various environmental indicators, and is flexible enough to be applied and support continuous improvement activities.

In addition, the consideration of environmental performance possibly impacts product sustainability which refers to three main dimensions such as *economic*, *social*, and *environment* (Hauschild, Jeswiet and Alting 2004). This indicates that the company has to produce a product or process not only of good quality to enhance customer satisfaction but also to be accepted socially and environmentally. It is clear that environmental performance evaluation must be an essential part of the product design and development process and continuous improvement effort.

1.4 Scope of the research

The scope of this research is to develop a flexible model for environmental performance evaluation, and integrating it into the product design and development process. This will be achieved by setting environmental indicators at the outset of the product design and development process. Environmental indicators, such as reprocessed materials, solid waste, energy consumption and wastewater treatment systems, are directly associated with the production process to meet the environmental requirements set by a manufacturing company. The main contribution of this research is to address a practical problem in a company related to design and development of environmental performance evaluation model. Further contribution of the research is explained in Chapter Seven in details.

1.5 Motivation of the research

With an increased demand for environmentally friendly products and public pressure from governments and stakeholders, environmental aspects which include environmental performance evaluation are of concern in the manufacturing industry to ensure they incorporate environmental aspects into their activities and circumstances. The

environmental issues and problems also have to be addressed by small-medium industries (SMEs). These industry are typically much smaller compared to large or multinational enterprises in operations (Rao *et al.* 2006) and, in practice, SMEs are the backbone of economic development. These industries can account for up to 80% of industry in developing countries where SMEs have been the main player in domestic economic activities as they account for more than 99.98 percent of all firms and employ 96.2 percent of the total workforce (Tulus Tahi Hamonangan 2011) and possibly influence job creation, job absorption and economic empowerment. Furthermore, these industries play an important role in developing the talents of villagers, particularly women, as entrepreneurs (39%). SMEs influence the percentage of female participation in business industry. Also contribution of SMEs to gross domestic product (GDP) is great with contribution ranging between 38 and 76 percent (Tulus Tahi Hamonangan 2011).

On the other hand SMEs, in practice, are not fully aware of environmental management even though they will gain many benefits by applying into their business activities (Rao *et al.* 2006). There is a need to build a collaborative link between these industries and educational institutions, researchers and governments to addresses their problems particularly in product design and development; currently only a small proportion of them improve their business activities via product design and development. These industries are less able to handle their product design and development process successfully in their own business activities (Berry, Rodriguez and Sandee 2001). Many SMEs are traditionally enterprises with low productivity, and the majority still need a diffusion of technology and knowledge transfer to improve their business activities and operations.

SMEs play a significant role in changing the work environment in the field of manufacturing, and most researchers argue that their operations have to be clean and green (Rao *et al.* 2006). There are four main concerns related to green manufacturing to be considered in these industries namely: the inputs to the process, the generation of waste (hazardous and non-hazardous), the waste disposal, and the recycling and reuse of packaging material (Rao *et al.* 2006). Also environmental performance evaluation systems need to be conducted in the SMEs to achieve the greening of industry.

The proposed model is expected to significantly enhance the understanding of the product design and development processes including environmental performance evaluation to lead to environmentally friendly products. The proposed model has two main benefits for industry including SMEs: firstly, assisting the expert team to determine the appropriate environmental indicators applicable to their business; and secondly, provide flexibility by allowing them to invite and include experts' knowledge.

This scheme can possibly be further modified and incorporated with other tools and approaches with subjective and qualitative information. This scheme is expected to be user-friendly and assist manufacturing industry, including SMEs, to produce greener products.

1.6 Thesis structure

This thesis is organised into seven chapters whose structure is shown in Figure 1.2 and a summary of each chapter is given below:

- Chapter One presents the research background where the importance of an eco-design concept for sustainable product development is presented. Environmental evaluation as important parts of the product design and development process are highlighted. The scope of the research is presented along with the motivation for undertaking this research.

- Chapter Two reviews the literature on the concepts and theories of environmental indicators, environmental performance evaluation, and environmental conscious design. The deficiencies of the literature are highlighted leading to the research gaps, research ideas, and research objectives.

- Chapter Three presents research methodology and tools for modelling of environmental performance evaluation. The concept of six sigma is presented and discussed along with tools and activities under six sigma approach followed by the concept of fuzzy logic and fuzzy inference system (FIS). The algorithm of design for six sigma (DFSS) from six sigma approach with IDOV (*identify, design, optimise, validate*) activities and FIS are proposed for development of the environmental performance evaluation model.

- Chapter Four describes the approach to modelling of environmental performance evaluation along with the related algorithm and tools of DFSS, as well as IDOV activities being integrated with fuzzy logic and FIS.

- Chapter Five presents modelling of environmental performance evaluation. The flow of IDOV activities related to design of the proposed model are explained in detail. The fuzzy QFD with environmental concern is explained in the first step to prioritise environmental indicators, then the selected indicators are set as input variables. A transfer algorithm is employed to develop the model followed by Taguchi's method to analyse the proposed model based on a statistical approach.

- Chapter Six presents a case study by applying the developed scheme to an Indonesian textile manufacturing industry to demonstrate the applicability of the scheme followed by a discussion on the limitations of the analysis.

- Chapter Seven presents conclusions of the research and culminates with recommendations for further work.

1.7 Concluding remarks

The importance of an eco-design concept for sustainable product development and environmental evaluation, as part of product design and development, were extensively discussed and highlighted here to substantiate the scope of the research supported by the motivation of the research. The research activities and outcomes were briefly outlined in the thesis structure. Finally the thesis structure is outlined.

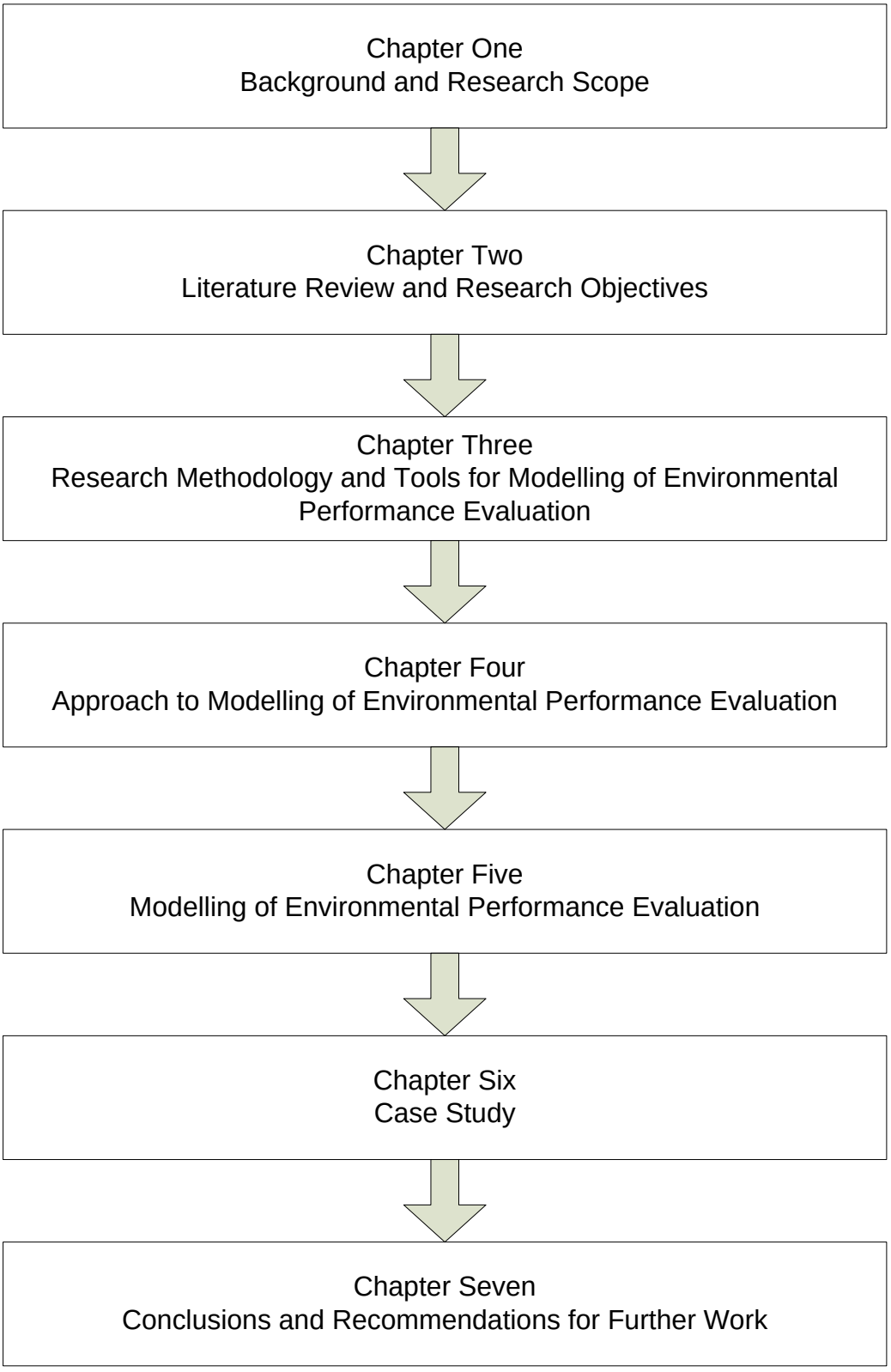


Figure 1.2 The writing architecture of the thesis

Chapter Two

Literature Review and Research Objectives



2.1 Introduction

This chapter describes a review of the current literature in the area of environmental performance evaluation of a manufacturing organisation. The review first describes and evaluates various environmental indicators followed by various approaches and studies for evaluating the environmental performance, then quality function deployment (QFD) from conscious design point of view related to design of environmentally friendly products is reviewed. Different indicators are used in literature such as *environmental performance indicator*, and *environmental management indicator*. In this research the focus of attention is on *environmental performance indicators* briefly referred to as *environmental indicators*; in other words, in this chapter they are used synonymously but in future chapters only the latter, *environmental indicators*, is used. The chapter ends with research gaps, research ideas and research objectives.

2.2 Environmental indicators

The basic concept of environmental performance evaluation (EPE) is to define, measure and analyse environmental (performance) indicators and compare them against the criteria set by an organisation. The purpose of EPE is thus to define, quantify and track selected environmental indicators in order to identify their impacts on the environment caused by the manufacturing organisation's operation. This evaluation can also help the organisation to identify opportunities for prevention, improvement and strategic business opportunities in the context of environmental performance. Environmental indicators are the key concept in the EPE. They provide information on the environmental impacts of an operation and the opportunities for improvement. The classification of various environmental indicators are presented in the following section.

2.2.1 Categories of environmental indicators

ISO 14013 standards recommends two main categories of environmental indicators, namely *environmental performance indicators (EPIs)* and *environmental condition indicators (ECIs)* (Jasch 2000). *EPI* provides information on an organisation's internal environmental performance. *EPI* can be divided into two categories, *management performance indicators (MPIs)* and *operational performance indicators (OPIs)*. MPI provides information associated with the effort of management to influence an organisation's environmental performance, while OPI provides information related to the

environmental performance of an organisation's operations. *ECIs*, on the other hand, provide information associated with the external environments such as the local, regional, national or global conditions.

There are many proposals and studies on environmental indicators. Henri and Journeault (2008) examined two classification of environmental performance indicators namely financial and non-financial indicators and ISO 14031 guidelines. Both financial and non-financial indicators can be captured in the various aspects of organisational effectiveness. The authors highlighted that the ends and outputs are revealed by financial measures while the means and processes are reflected by non-financial measures such as monetary resources invested in the environment, atmospheric emissions, wastewater, the number of environmental audits, and the number of environmental non-compliance incidents.

According to Jasch (2000) data used for environmental indicators can be expressed as absolute or relative measurements, can be aggregated or weighted that depends on their use and application. These data can be gathered at the level of a company, departments, cost centres or separate machines. The author highlighted there are some purposes of environmental indicators such as periodically comparing environmental performance, highlighting to optimisation potentials, associated with environmental targets, cost reduction potentials, benchmarking on environmental performance evaluation between firms and a tool to communicate environmental reports. Furthermore the author highlighted that there are some principles to derivate environmental indicators such as comparability, target-oriented, balanced, continuity, frequency and comprehensibility.

According to Thoresen (1999) there are three categories of environmental performance namely, *Product Lifecycle Performance*, *Environmental Performance of Selected Process Technology* and *Environmental Performance of Operations*. *Product Lifecycle Performance* considers environmental impacts caused by the use of resources, transport activities and the performance or environmental implications of products and packaging along the product life cycle. *Environmental Performance of Selected Process Technology* depends on the manufacturer's choice between alternative technology options. *Environmental Performance of Operations* is concerned with environmental impacts resulting from all on-site manufacturing and management processes. The author provided

the categories and sub-categories of environmental performance to guide the construction of environmental performance indicators as depicted in Table 2.1.

Table 2.1 The example of environmental indicators categories and sub-categories to guide the construction of EPI (Thoresen 1999).

Indicators
A. Product lifecycle performance indicators - Energy, materials and resource consumption - Distribution/transportation - Customer use - Waste treatment * Reuse * Recycling * Incineration * Deposition
B. Environmental performance of operations indicators: - Environmental management system performance - Financial consequences of environmental action B.2. Manufacturing operations performance indicators - Energy planning * Total energy consumption * Energy mix * Consumption of non-renewable energy sources * Energy efficiency - Procurement planning * Supplier selection * Surveillance of suppliers' performance - Transport planning * Transport media selection * Environmental performance of transport media in use - Production planning * Rejects and material waste performance - Production * Environmental performance of processes * Number and consequences of environmental incidents

Rao *et al*. (2006) divided environmental indicators into three main groups depending on where these indicators will be addressed such as the company's environmental performance/impact, the management's environmental activities, or the external condition of the environment. Examples of environmental indicators proposed by them are illustrated in Table 2.2. The three categories of these indicators are *environmental performance indicators (EPI), environmental management indicators (EMI), and*

environmental condition indicators (ECI). Also the authors pointed out that the use of these indicators can guide the company in decision-making to measure precise information on matters such as water usage, air emission, and energy consumption to determine the actual environmental performance. The authors also highlighted that the main important features of environmental indicators are: they can quantify important development in the corporate environmental initiatives and also can provide a framework for comparing them periodically.

Table 2.2 The example of environmental indicators (Rao *et al*. 2006)

<table>
<tr><th>Environmental performance indicators (EPI)</th><th>Environmental management indicators (EMI)</th></tr>
<tr><td rowspan="4">Input indicators (materials)
consumption/output ratio
raw material efficiency
packaging to output ratio
reusable packaging ratio
hazardous material ratio
recyclable raw materials ratio</td><td>environmental investment
environmental cost</td></tr>
<tr><td rowspan="3">Training/staff
training on environmental issues</td></tr>
<tr><td>Input indicators (energy)
energy cost ratio
energy consumption ratio
renewable energy ratio</td></tr>
<tr><td>Input indicators (water)
water consumption ratio</td></tr>
<tr><td>Output indicators (waste)
total waste to output ratio
recycling waste ratio
waste for disposal ratio
hazardous waste ratio
specific waste ratio</td></tr>
</table>

Tsoulfas and Pappis (2008) stated that environmental performance indicators refer to a set of sustainability indicators focusing on the long-term effects of a policy in an area or country. Although there are many characteristics and categories of environmental performance (EP), the authors stated that it is necessary to extend these characteristics to make them appropriate, suitable, coherent, measurable and verifiable. They proposed six groups for EP indicator classifications namely: *product/process design and production, packaging, transportation (distribution and recovery), recycling and disposal, greening*

the internal and *external business environment*, and *other management issues* whose examples are depicted in Table 2.3.

Table 2.3 The example of proposed indicators (Tsoulfas and Pappis 2008)

Proposed indicators for product/process design and production	**Proposed indicators for packaging**
Materials	Size
Recyclability	Recyclability
Reusability	Reusability
Energy consumption	Energy consumption
Energy sources	Energy sources
Fresh water use	Fresh water use
Water reuse	Water reuse
Use of recycled materials	Use of recycled materials
Standardization	Standardization
Disassemblability	By-products
By-products	By-products' reuse
By-products' reuse	Defects
Defects	Defects' reuse
Defects' reuse	Production waste
Production waste	Biodegradable products
Biodegradable products	

Ren (2000) proposed the methodology for EPI development based on process and product perspectives as depicted in Figure 2.1.

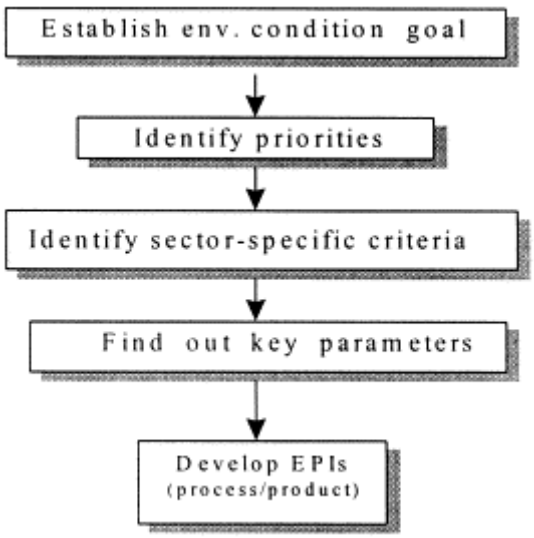


Figure 2.1 Methodology for developing EPIs (Ren 2000)

This methodology consists of five steps namely: establish environmental condition goals, identify priorities, identify sector-specific criteria, find out key parameters, and develop EPI. These indicators need to be prioritised as per individual companies goals, objectives and the interest of stakeholders.

Kolk and Mauser (2002) presented the three components of environmental indicators as depicted in Figure 2.2, namely: *environmental management indicators (EMIs), environmental condition indicators (ECIs)* and *environmental performance indicators (EPIs).* The authors divided the performance indicators into *operational indicators* and *impact indicators*. *Operational indicators* refer to the indicators related to areas such as procurement, production process and the use and disposal of products while *impact indicators* refer to the output such as emission and waste.

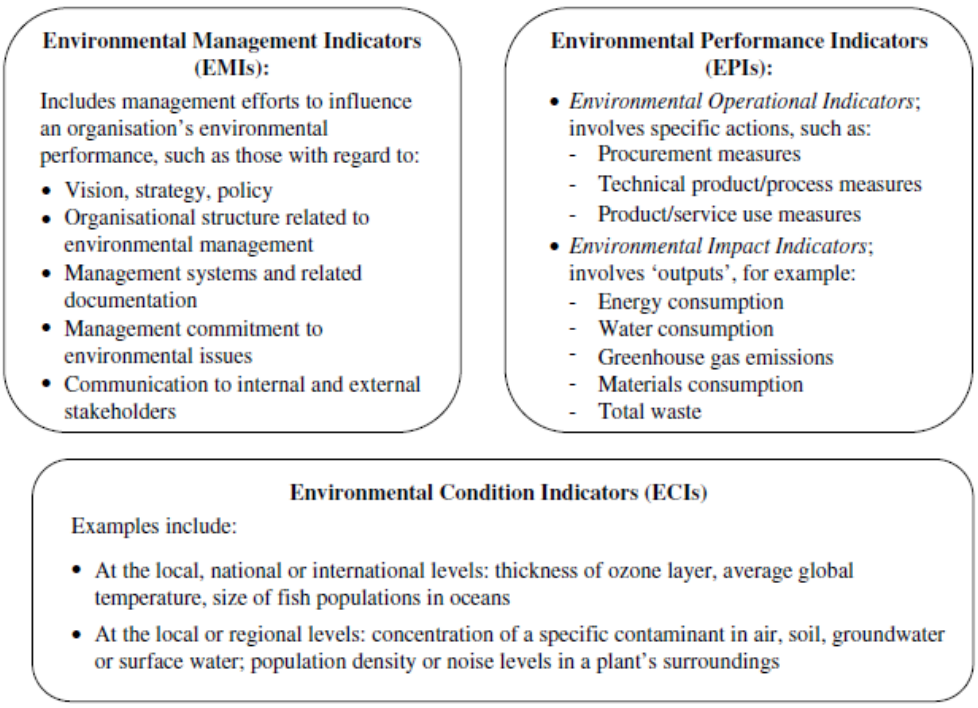


Figure 2.2 Components for environmental performance evaluation (Kolk and Mauser 2002)

Papadopoulos and Giama (Papadopoulos and Giama 2007) stated the two main types of indicators used for environmental evaluation namely: *environmental condition indicators* (*ECI*), *environmental performance indicators* (*EPI*) which are subdivided to *management performance indicators* (*MPI*). These indicators set based on ISO 14031 guidelines as depicted in Figure 2.3.

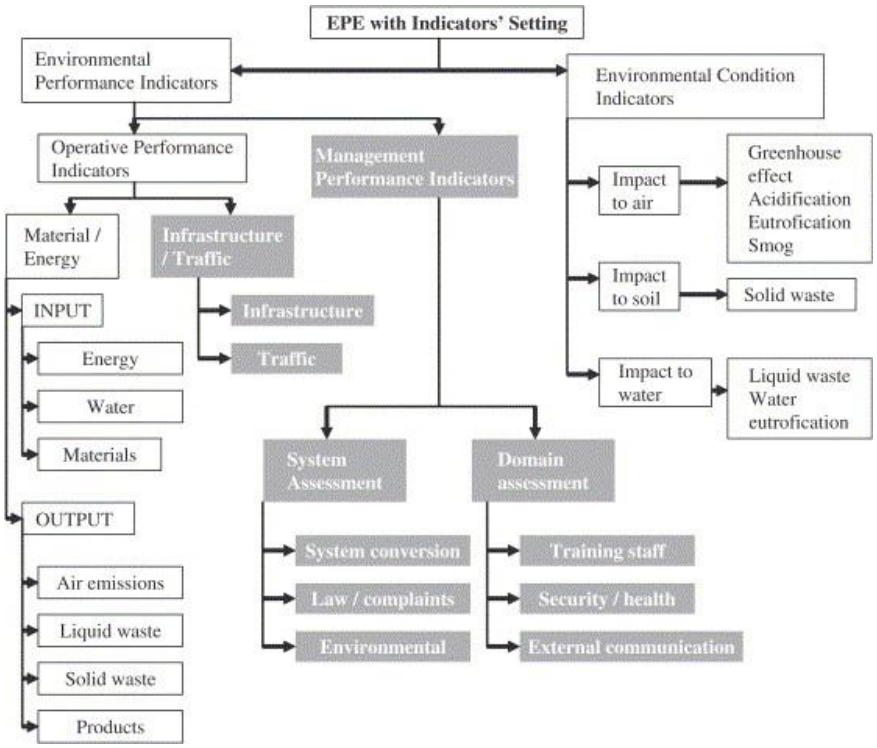


Figure 2.3 Indicators for environmental performance evaluation (Papadopoulos and Giama 2007)

2.2.2 Main issues of environmental (performance) indicators

The general consensus of the reviewed literature is that the selection process of environmental indicators can be derived from the internal and external organisation. Internal organisation indicates the area where the environmental performance is based on the internal activities such as production process. These indicators should describe and control the environmental performance of their products and individual activities or processes inside the company.

External organisation indicates the area where the environmental performance is to support the stakeholder's requirements to improve environmental negative impacts of the company. These indicators are needed to put pressure on the company or organisation and make sure that improvement actions have been planned and implemented on a continuous basis (Thoresen 1999).

The identification of these indicators may vary and differ from one company to another as it depends on the type of their products, processes, organisation's management and policy. The identification of them is important and indicates how much the company is concerned on environmental issues. The environmental indicators are to be prioritised to

identify the ones appropriate for the company's circumstances and environmental goals. Many researchers have identified different categories of environmental indicators but there is a lack of guidelines, or even recommendations, on how a specific organisation will prioritise and apply the significant indicators to fulfil their environmental requirements and environmental business goal (Niemeijer and de Groot 2008).

Most researchers maintain that EPIs are primarily a means for external stakeholders to influence manufacturing companies to move in a sustainable direction from outside and environmental indicators from inside the company, such as at product design and development processes, have a great influence on the environmental performance of the company, i.e. companies can achieve environmental improvement as long as their environmental indicators are from within the company (Olsthoorn *et al*. 2001; Thoresen 1999).

There are two main reasons why it is important to set EPI for internal stakeholders. Firstly, these indicators can be used as an internal goal setting to control and monitor a product or process (primary and sub-processes) performance inside the company. Secondly, product and environmental improvements actions can be triggered by benchmarking vs competitors' performance (Thoresen 1999). The main purpose of identification of EPI is not only for EPE purposes but also there are other advantages such as EPI can assist a company in selection of environmentally friendly techniques, benchmarking, environmental reporting and support establishment of environmental management system/EMS (Ren 2000).

To identify appropriate indicators for an EPE process, the organisation has to compile a list of indicators by following the general guidelines of the ISO 14031 standard and linking them to the corresponding environmental aspects. EPI for external and internal aspects must be correlated to address the same environmental and effect categories, but may be expressed at different levels of aggregation and in different formats according to stakeholder requirements. The identification of these indicators should be objective, under-standable, significant, meet the objectives and responsive to stakeholders (Olsthoorn *et al.* 2001). The selection of appropriate indicators will have a great implication on environmental performance. These indicators can provide an important source of information associated with what has been occurring and help the decision-

making team in the organisation to analyse the problems and develop appropriate actions for improvement (Niemeijer 2002).

Finally, in practice, there is still a need to determine which environmental indicators of the entire system are mostly associated with the environmental business goal of the organisation so that they will be monitored and modelled. It is necessary to design a systematic approach which can be followed by industry to help them determine indicators that best reflect the environmental impacts of the company.

2.3 Environmental performance evaluation (EPE)

As explained in Section 2.2 the main aim of an EPE process is to measure and analyse environmental performance indicators and compare these with criteria already set by organisational management. Also EPE is to ensure that manufacturing or industrial activities, including production process and product design development, would move towards sustainable development (Thoresen 1999). Some approaches and methods have been conducted to evaluate environmental performance and will be explained in the following section.

2.3.1 Environmental performance evaluation approach

Several approaches to EPE have been extensively conducted and covered many areas of industry, such as statistical approaches, the concept of life cycle assessment (LCA), analytical hierarchy process (AHP), multi criteria decision-making (MCDM), risk management, data envelopment analysis (DEA), balanced scorecard (BSC) and quality function deployment (QFD) approach.

Some researchers applied some statistical approaches and used the analysis to measure and evaluate environmental performance. Corbett and Pan (2002) used statistical process control techniques to evaluate environmental performance. The authors proposed the cumulative sum (CUSUM) chart as a tool to monitor emission data and process capability index to evaluate environmental performance and pointed out that these charts were useful for environmental process management and monitoring as well as emissions monitoring.

Rao *et al.* (2006) presented the use of a survey questionnaire followed by structural equation modelling (SEM) to evaluate and validate an environmental performance model. The study demonstrated how environmental indicators significantly correlated with the environmental performance by developing a structural model consisting of three latent constructs namely: environmental performance indicators (EPI), environmental management indicators (EMI), and environmental performance. The authors examined the correlation of EPI, EMI with a firm's environmental performance as depicted in Figures 2.4 and pointed out that environmental management decisions taken by the company's management and captured by the latent construct EMI significantly led to specific environment initiatives, as captured by the latent construct EPI and led to actual environmental performance.

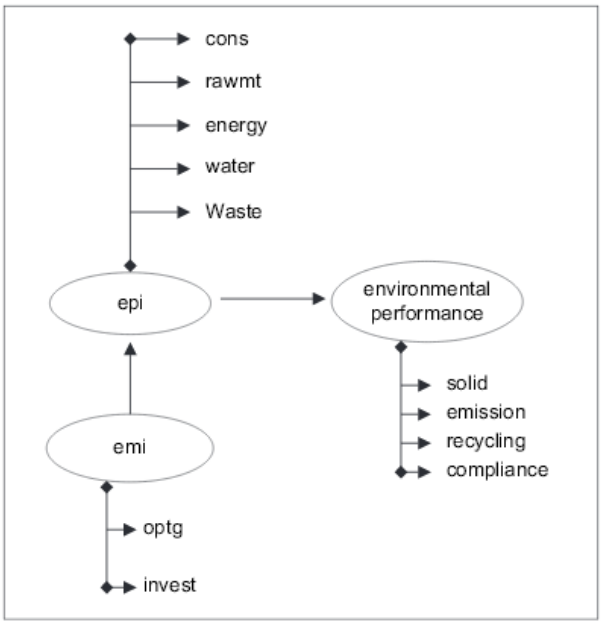


Figure 2.4 The structural model to show EMI leading to EPI which leads to environmental performance (Rao *et al.* 2006)

Seroa da Motta (2006) presented the use of regression analysis to evaluate environmental performance and proposed the environmental performance as a dependent variable. The author used three independent variables: the *firm's compliance costs*, given by marginal pollution control cost, reflecting the ability to comply with terms of the firm's characteristics, the *market incentives* to increase environmental performance due to their effects on competitiveness, and *non-compliance marginal costs* related to the sanctions applied by regulators.

Henri and Journeault (2008) presented the measurement of environmental performance indicators within manufacturing firms by using a survey design. A random sample of manufacturing organisations was formed and then the questionnaire was structured by using a seven-point Likert-type scale. The authors used correlation matrix and analyses of variance (ANOVAs) to examine the importance of environmental performance indicators.

Srebotnjak (2007) examined the role of statisticians working on the environmental statistics and policy within the context of measuring environmental performance. The author pointed out that as experts (on the collection, analysis and interpretation of statistical information) environmental statisticians can create and analyse the information to determine policy choices and build the regulatory framework. Furthermore by providing scientific evidence they can support decision makers in weighing alternatives and balancing objectives. The study proposed six policy objectives with their indicators as depicted in Figure 2.5 and also involved expert judgment to build the model.

Policy objective	Indicators contained in policy objective	Performance target for the indicator
Environmental health	• Indoor air pollution	0% of households
	• Access to drinking water	100%
	• Adequate sanitation	100%
	• Child mortality	0 deaths/1000 children 1–4years
	• Particulates concentration	10 $\mu g/m^3$
Air quality	• Particulates concentration	10 $\mu g/m^3$
	• Regional ozone concentration	15 ppb
Water resources	• Nitrogen loading	1 mg/l
	• Water consumption	0% oversubscription
Biodiversity and habitat protection	• Water consumption	0% oversubscription
	• Wilderness protection	90% of wild areas protected
	• Eco-region protection	10% for all biomes
	• Timber harvest rate	3%
Natural resources productivity	• Timber harvest rate	3%
	• Agricultural subsidies	0%
	• Overfishing	Score of 0 (no overfishing)
Sustainable energy	• Energy efficiency	1650 TJ/million US$ GDP
	• Renewable energy	100%
	• CO_2 emissions	0 net emissions

Note: The indicators particulates concentration, water consumption, and timber harvest are each constituent to two policy objectives. They and their corresponding performance target are therefore listed twice. The total number of indicators in the EPI is 16.

Figure 2.5 The EPI's six policy objectives, its indicators, and corresponding performance targets (Srebotnjak 2007)

Diakaki, Grigoroudis and Stabouli (2006) presented a risk assessment approach for selecting environmental performance indicators. The proposed method started from the identification of a set of indicators where each indicator is identified to monitor and assess

the progress achievement of an organisation's goal related to environmental aspects. The environmental risk is calculated based on the evaluation of the frequency of failure to achieve the related goal, the probability of a resulting negative impact and the significance of this impact.

Dias-Sardinha and Reijnders (2005) used balanced score card (BSC) to evaluate environmental and social performance. Financial aspects of environmental and social company activities were involved in this study. Three categories of performance namely: compliance with the law while emphasising pollution control, pollution prevention and eco-efficiency were also included. The authors pointed out that using this approach is useful to better understanding the strengths and weaknesses of the links between objectives and measurements, initiatives and achievements. This study found that the improvement on environmental and social performance will be achieved simultaneously.

Similarly Hsu and Liu (2010) used BSC to evaluate environmental performance and strategy management and a survey was conducted. Using some statistical analysis the authors described the performance measures and the application potential of BSC and then argued that the use of BSC is strongly recommended to establish and ensure proactive environmental strategy. The authors highlighted that there are many benefits of adopting BSC in the environmental strategy management such as:

- can provide complete performance and perspectives;
- support effective management system;
- consider internal/external, financial/non-financial, driving/outcome key performance indicator (KPI) in a balanced way; and
- implement BSC and generate synergy with other corporate strategy management.

Other qualitative methods such as surveys, questionnaires and interviews have also been used to evaluate environmental performance. Tam *et al.* (2006) pointed out that performance measurement indicators (PMIs) are required to implement environmental performance assessment (EPA). The study began by conducting a structured survey in the form of a questionnaire and interviews. The authors identified three key output indicators namely: regulatory compliance, auditing activities, and resources consumption. The study also examined nine sub-indicators such as: fines and penalties, complaints/warnings, non-compliance records of inspection, non-conformance reports,

and reports of marginal cases. To analyse the results from each respondent they determined the mean values for each group and used it to test concordance between groups and F-test.

Zhou, Poh and Ang (2007) demonstrated the use of a weighting scheme based on data envelopment analysis (DEA) concept to evaluate and measure environmental performance. This concept extensively uses nonparametric linear programming techniques for evaluating the performance of comparable production units such as companies or non-profit organisations. The DEA concept has gained popularity in environmental performance measurement due to this concept that can provide a synthetic standardised environmental performance index when pollutants are suitably incorporated into the traditional DEA framework.

Munksgaard *et al.* (2007) proposed a bridging gap between environmental indices related to physical pressure and damage costs. In this study damage costs referred to a range of damage cost estimates for each pressure type considered. Their design of analysis with and without damage cost restriction is depicted in Figure 2.6. Two main considerations of this study are to implement the information on environmental damage costs within DEA based on an environmental performance index, and to estimate these indices at the product level by using Danish input-output data. The methodology used in this research is a combination of input-output modelling with DEA to estimate an environmental performance index. A static input-output model was used encompassing direct and indirect emissions embodied in products consumed by households. The author pointed out that by introducing damage cost restriction in a DEA concept the possibility to determine extreme weights of 100% can be eliminated.

Similarly, the concept of DEA analysis has been applied to evaluate environmental efficiency at oil refineries (Bevilacqua, Maurizio and Braglia 2002). Air emission was determined as an environmental impact in their study. The DEA is proposed as an objectives benchmark as this technique can evaluate the relative environmental efficiency by considering six different types of emissions such as CO, CO_2, and SO_2.

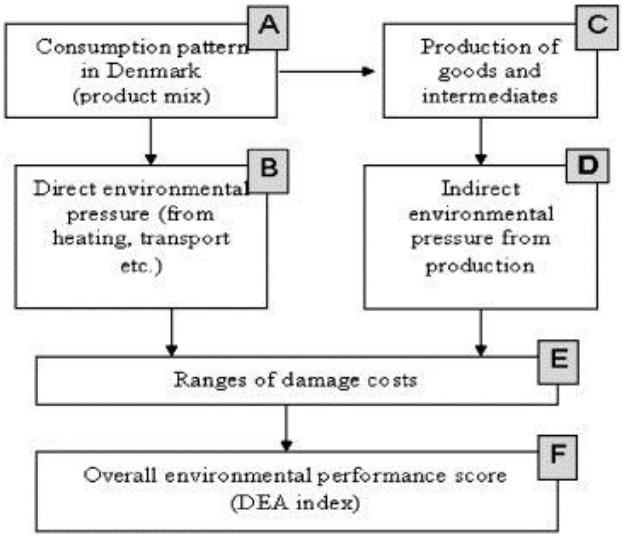


Figure 2.6 Design of analysis with and without damage cost restriction (Munksgaard *et al.* 2007)

Kortelainen (2008) used DEA concepts to construct an environmental performance index. The study presented how environmental performance index can be elaborated into two components namely: environmental technical change and the relative eco-efficiency change. The author also pointed out that the environmental technical change index can be deployed into two main different indices namely: as a product of the magnitude change index and the environmental bias index. These indices will be useful when analysing the sources and reasons for changes in environmental performance over the time. In addition, several approaches using DEA concept to evaluate environmental evaluation have been conducted to monitor air emission as undesirable output (Färe, R., Grosskopf and Hernandez-Sancho 2004; Färe, Rolf, Grosskopf and Pasurka 2010; Zhou, P., Ang and Poh 2006; Zhou, Peng, Poh and Ang 2007).

Jia, Han and Tan (2004) used multi criteria decision making (MCDM) and analytical hierarchy process (AHP) concepts to evaluate environmental performance assessment of chemical processes, stressing that the quantitative analysis of environmental performance is required during the process design. The authors developed integration of process design and the performance assessment was developed. Process environmental performance assessment (PEPA) as a tool to select the environmentally friendly process alternative by evaluating environmental performance is depicted in Figure 2.7. The authors used nine categories of environmental impact such as global warming potential (GWP), photochemical oxidation (PO) and ozone depletion potential (OD). The aggregating

criteria was considered as a hierarchical MCDM problem and analytic hierarchy process (AHP) was conducted to solve the problem.

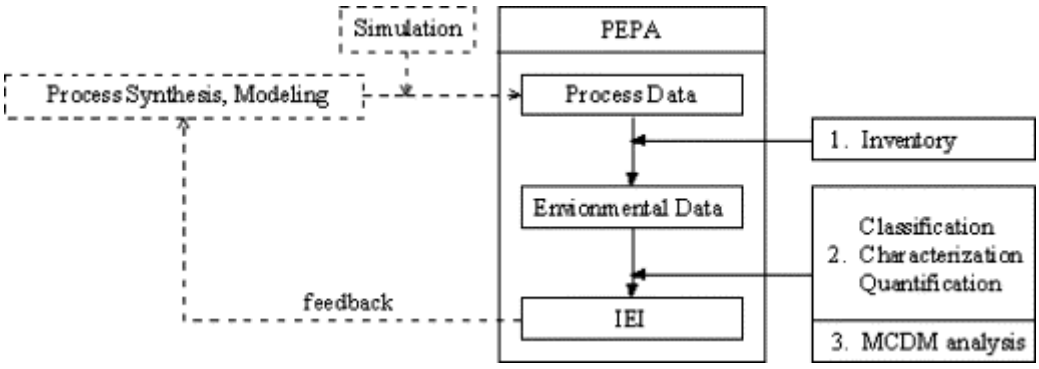


Figure 2.7 Conceptual framework for PEPA (Jia, Han and Tan 2004)

Vandermeulen *et al*. (2003) proposed a methodology which was based on traditional LCA as a complete method based on performance indicators for eco-efficiency of products. The authors pointed out that the main advantage of this concept is that the design team, including environmental coordinators and project managers, can calculate and evaluate indicator scores for very specific environmental aspects. The design team can actually customise the assessment according to their own priorities and policies, or tune it to the customer's requirements. A set of environmental indicators were used in this study such as amount of prohibited materials, amount of restricted materials, component complexity, and possible hazardous waste rate.

Similarly, Ana Claudia *et al.* (2004) used LCA concept to evaluate environmental performance and focused on the air emission with its impacts such as global warming (GW). Pineda-Henson, Culaba and Mendoza (2002) demonstrated the evaluation of environmental performance by using the integration of AHP and LCA. The authors pointed out that LCA can offer a comprehensive and systematic framework within different stages of manufacturing processes. AHP was applied to estimate the weighting factors for different environmental impacts and improvement options. In this study natural resource depletion, human toxicity, ecological toxicity and greenhouse effect were identified as environmental impacts. Their theoretical framework is depicted in Figure 2.8.

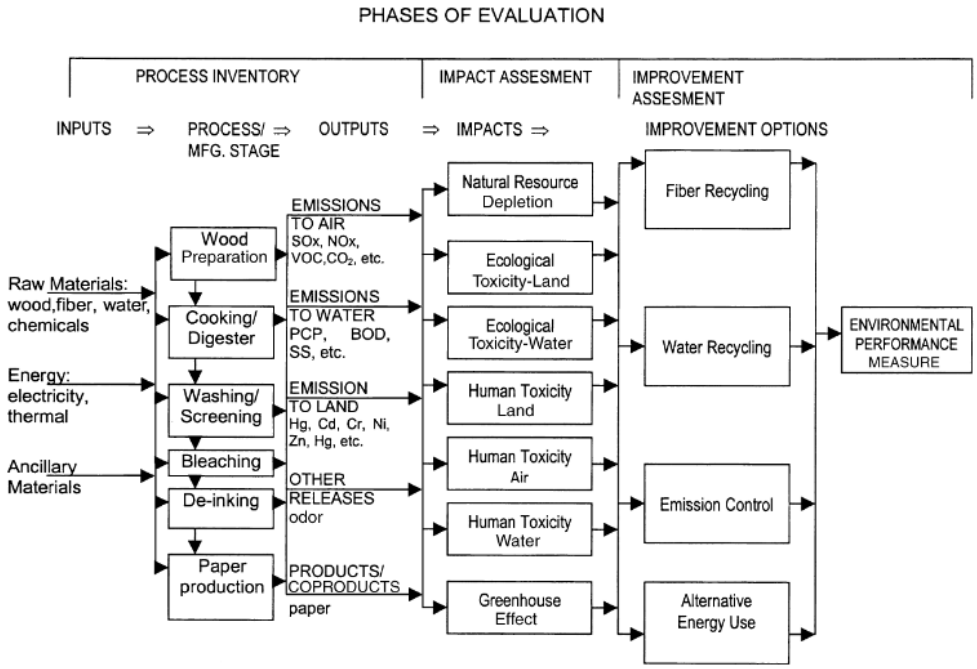


Figure 2.8 Theoretical framework of environmental performance evaluation (Pineda-Henson, Culaba and Mendoza 2002)

Montanari (2004) demonstrated using MCDM and the technique for order of preference by similarity to ideal solution (TOPSIS) analysis to estimate environmental efficiency at thermo power plants (TPPs). In this study environmental efficiency was defined as a function of consumption, cost, and emission (SO_2, NOx, ash, and CO_2). The MCDM was applied to rank the TPPs as a function of the environmental efficiency, and TOPSIS was used to categorise the plants according the six different criteria such as specific consumption, specific-fuel cost, SO_2 emissions, NO_x emissions, ash emissions, and CO_2 emissions.

Tsoulfas and Pappis (2008) classified several sets of environmental performance indicators into six groups, namely: product/process design and production, packaging, transportation (distribution and recovery and collection, recycling and disposal, greening the internal and external business environment, and other management issues) to analyse supply chain performance. The authors proposed a decision model based on environmental performance. The authors used MCDM and highlighted that this approach can provide a systematic analysis, help the decision makers in identifying their most desired solutions, and it is transparent, non-ambiguous and easy to use by non-experts.

Herman, Kroeze and Jawjit (2007) presented the evaluation of environmental performance by using the combination of LCA, multi criteria analysis, (MCA) and environmental performance indicators (EPIs). The study began by providing performance indicators for selected resources and emissions associated with production output. Then LCA was conducted to calculate the potential of environmental impacts while AHP was used to establish weight for selected criteria. Environmental impacts in this study referred to air and water emissions based on direct emissions and raw materials consumption.

Awasthi, Chauhan and Goyal (2010) presented the evaluation of environmental performance of suppliers using fuzzy multi-criteria approach. The proposed design begins with identification of criteria for assessing environmental performance then the experts evaluate the selected criteria and their alternatives (suppliers), then linguistic assessment and fuzzy approach are employed to quantify the expert's judgments. The authors maintain that the main advantage of this approach is that it is practical and has the ability to provide solutions under partial or lack of quantitative information.

Concepts which integrate MCDM and fuzzy concept also have been used to evaluate green suppliers with environmental criteria. Tuzkaya *et al.* (2009) proposed a hybrid fuzzy multi-criteria decision methodology for evaluating suppliers with environmental criteria. In this study the authors demonstrated the integration of fuzzy-analytic network process (F-ANP) and fuzzy-preference ranking organisation method for enrichment evaluations (F-PROMETHEE). ANP is a comprehensive decision-making technique that has the capability of including all the relevant criteria which have some bearing on arriving at a decision. Triangular fuzzy numbers (TFNs) was used to evaluate the decision maker's preferences. Similarly, Shen *et al.* (2013) used fuzzy multi-criteria with linguistic preferences to evaluate green supplier's performance in green supply chain. TFNs were also used to assess the preference.

Büyüközkan and Çifçi (2012) demonstrated the integration of MCDM and fuzzy concept to evaluate green suppliers. The authors examined green supply chain management (GSCM) and its capability dimensions to evaluate a framework for green suppliers. Five criteria of green suppliers were considered in this study namely green logistic dimension, green organisational dimension, organisational performance dimension, green supplier

evaluation criteria, and green supplier alternative. Furthermore the authors proposed and demonstrated a novel hybrid fuzzy MCDM to evaluate green suppliers.

Fuzzy concept is also used into waste recycling programs to propose a model of environmental performance assessment (Nasiri and Huang 2008) where the environmental performance index, referred to a *score value* and derived from certain economic and environmental parameters and indicators were used. The authors developed this index into two main directions namely efficiency and effectiveness then both were compared to the environmental benefits of a program as the output program to evaluate and assess the performance. A set of environmental benefits (energy saving, avoiding greenhouse gases, avoiding smog, avoiding litter, and avoiding landfill space) was developed and the fuzzy approach and linguistic terms were employed to assess these environmental objectives.

Barbiroli and Raggi (2003) proposed a quantitative method of classifying cleaner production innovations based on technical and economic criteria by dividing the methodology into two main levels (technical and economic). The main aim of technical levels is to identify a number of environmentally relevant technical aspects for the various stages of product life cycle. A list of selected aspects in the technical level were identified such as raw materials, energy, auxiliary materials, water used, waterborne emissions, atmospheric emissions from the production cycle, atmospheric emissions from the energy cycle, hazardous and toxic wastes, and solid waste. Some typical performance indicators were measured in the economic level to obtain a more comprehensive assessment of given information.

Brent and Visser (2005) determined three operational parameters namely: water use, energy use, and waste product to propose an environmental performance resource impact indicator (EPRII) to evaluate and assess suppliers. The calculation of an overall indicator of a company or manufacturing process can be identified on the four resource groups as depicted in Figure 2.9.

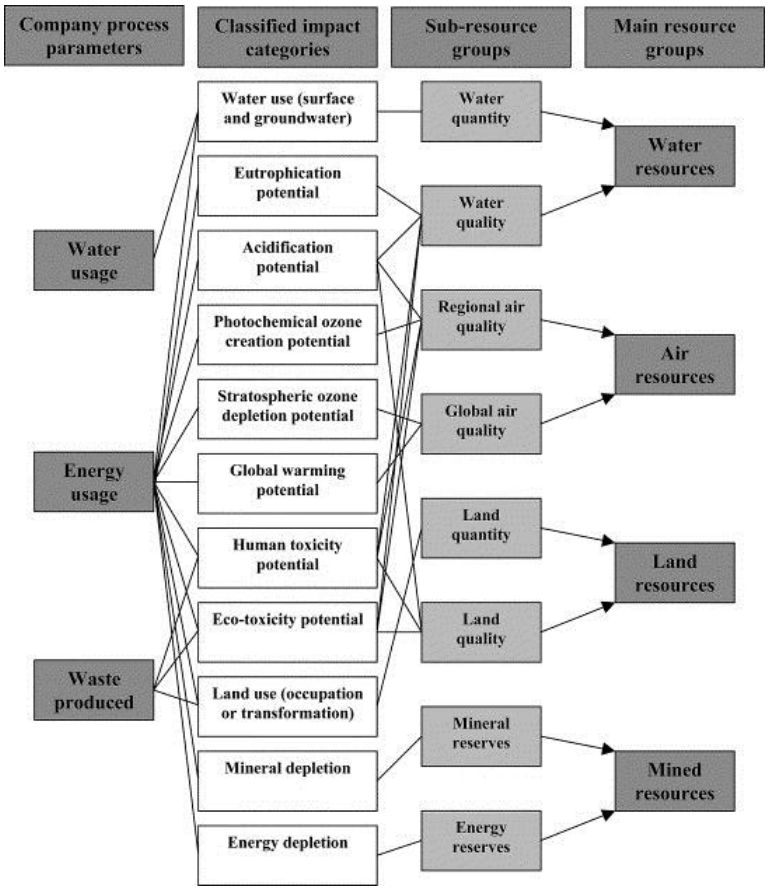


Figure 2.9 Framework to calculate the RII values (Brent and Visser 2005)

Siracusa, La Rosa and Sterlini (2004) proposed a new approach to calculate the environmental protection index (E_P) which was applied to evaluate the environmental pollution risk of a company to improve their environmental performance. The main aim of this method was to apply the E_p index in the environmental impact assessment system to quantify the risk of pollution of the entire process and to determine the most hazardous operations of the productive cycle while proposing possible solutions.

Perotto *et al.* (2008) used indicators and indices to evaluate specific environmental aspects (wastewater discharge). They used a list of some possible indicators from environmental management system (EMS) implementation (environmental analysis) report and these indices were chosen by considering the importance of monitoring performance in the EMS context.

Tam *et al*. (2004) focused on the measurement of environmental performance in the construction industry. They proposed the green construction assessment (GCA) for

environmental management in the construction industry. Two types of environmental indicators (management performance indicators/MPIs and operational performance indicators/OPIs) were involved, and MCDM and fuzzy approach were conducted. The authors concentrated on four objectives namely reviewing the environmental assessment tool for construction activities, developing a set of indicators/criteria, formulating weightings for all indicators, and verifying by application on real life projects.

Similarly, Tam *et al.* (2006) also presented environmental performance measurement indicators in construction. They used environmental performance assessment (EPA) as a critical tool for the environmental management system (EMS) to check, review, monitor, and evaluate environmental performance of an organisation. A structured survey, questionnaire, and interviews were conducted and three types of output indicators namely: regulatory compliance, auditing activities, and resources consumption were established. Within the same area of application Yao *et al.* (2007) presented a fuzzy analysis based scoring (F-EPS) method for measuring contractor's environmental performance. The authors identified eleven environmental performance indicators (air pollution, noise and vibration pollution, water pollution, construction and demolition waste, chemical waste, material storage leakage/spillage, dangerous goods, flora and fauna protection, land contamination, site cleanliness, and environmental management system) and proposed a framework of benchmarking. The authors pointed out that the measurement of environmental performance involved a fuzzy process as the control of pollution is usually difficult to quantify via a set of values.

Shen *et al.* (2005) used a computer based scoring method for measuring environmental performance. A case study in construction activities was presented and the environmental performance calculated by the contractor's environmental score (EPS). An information technology (IT) supported program was developed to calculate the EPS and also to assist contractors in diagnosing the cause of possible poor environmental performance.

In addition, a concept of quality function deployment (QFD) which is well known as a powerful method for product design and development processes have also been employed to assess environmental performance. QFD is a structured system of planning and development which enables the development team in companies to assess the proposed system systematically in terms of how it meets customer needs and requirements.

Defining requirements to increase sustainable product development means that not only technical and economic needs should be involved and assessed in the product development process but also environmental and social issues. The extended QFD which involves environmental requirements and impacts is used to address considerations relevant to environmental performance evaluations.

Utne (2009) used QFD concept to improve environmental performance of a fishing fleet. The authors pointed out that QFD can translate stakeholder's needs into detailed system requirements. The author used the concept of eco-QFD to integrate QFD, LCC and LCA to evaluate environmental effects and costs in the system development process. To construct the HOQ, the stakeholders needs will be derived based on management and technical responses as depicted in Figures 2.10 and 2.11.

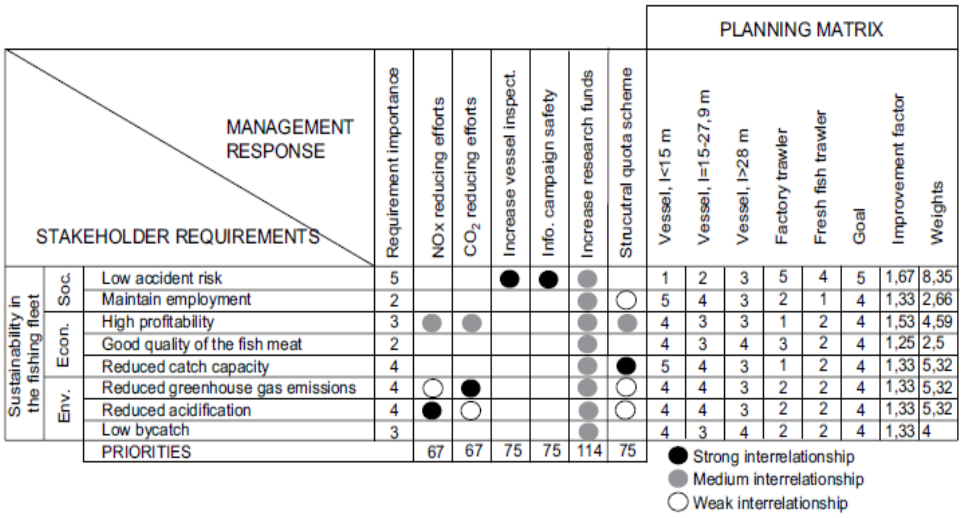


Figure 2.10 HOQ for management responses to improve sustainability in the fishing fleet (Utne 2009)

Halog, Schultmann and Rentz (2001) proposed and demonstrated the use of QFD for technique selection for optimum environmental performance improvement. The authors developed and applied a modified QFD to identify the emissions which have to be analysed related to environmental performance improvement; and developed a mathematical model to evaluate the emissions need to be deployed for further analysis associated with a budget cost constraint. The proposed modified HOQ in this study, called House of Ecology (HOE), is depicted in Figure 2.12.

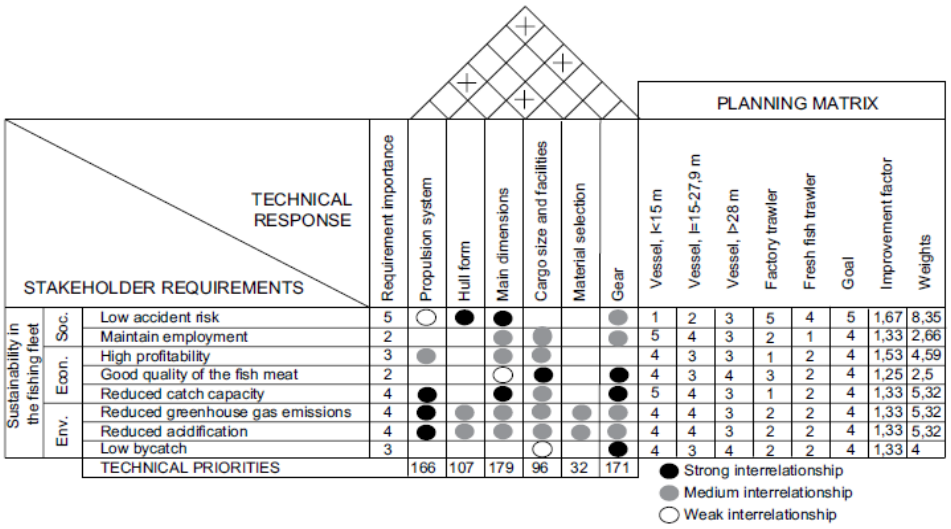


Figure 2.11 HOQ for a sustainable fishing fleet and technical responses (Utne 2009)

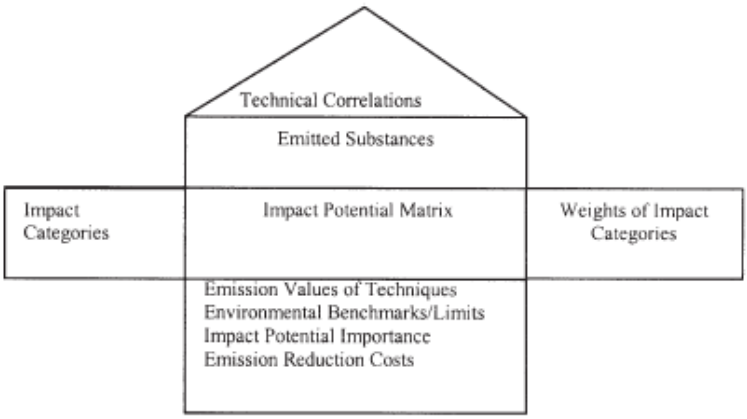


Figure 2.12 House of Ecology (Halog, Schultmann and Rentz 2001)

Yang *et al.* (2011) proposed a rough set-based QFD approach for environmental performance evaluation. Their research was deployed into five main steps namely: describing environmental requirements, determining favourable outcomes corresponding to the requirements, identifying required activities or issues to achieve the outcomes, searching for the proper measures of the activities or issues and generating a list of key indicators. Their methodology was divided into two main stages namely: identification of key indicators and environmental performance evaluation as depicted in Figure 2.13. Stage I focused on the identification of performance and condition indicators while stage II focused on the evaluation of the environmental performance of current and historical operations based on the indicators that have been identified in stage I.

2.3.2 Main issues in environmental performance evaluation approach

As explained in Section 2.3.1 environmental indicators and environmental performance evaluation have been analysed and measured through several tools, approaches and other statistical based methods which incorporates the environmental issues.

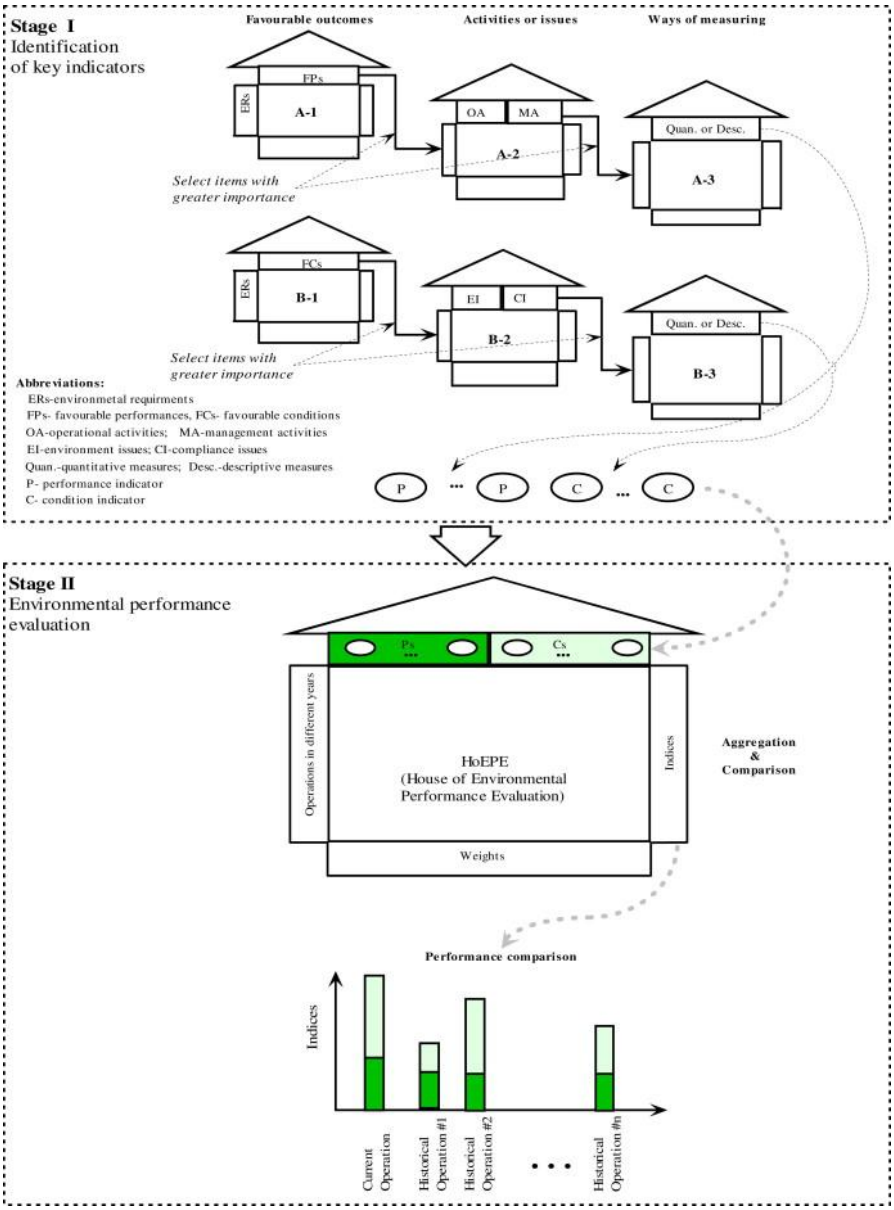


Figure 2.13 Rough set-based QFD approach for environmental performance evaluation (Yang *et al.* 2011)

A shortcoming of environmental performance evaluation is that most of these evaluations were conducted on the basis of the external operation of the organisation such as measurement on emissions with indicators related to greenhouses gases. The undesirable output (emission) is a main concern in these evaluations. Although some researchers

argued that the selection of indicators for the EPE purpose have to start from inside the company and be linked to external aspects and focus on the improvement effort on life cycle impact (Olsthoorn *et al.* 2001; Thoresen 1999) still less attention has been paid to the internal indicators of the organisation and setting them as improvement target. The internal environmental indicators of a company can lead to better achievements outside the company, so there is a need to consider internal environmental indicators to help companies to evaluate their processes related to their external requirements.

Other criticism is that the application of this evaluation was conducted with no link to product design and development processes, and also did not support continuous improvement effort (Kaebernick, Kara and Sun 2003). This evaluation needs to be integrated with product development activities; this implies consideration of environmental indicators as an integral part of the product development process and to support continuous improvement efforts (Shane 2003).The environmental performance needs to be integrated, as operation objectives, into the new paradigm of operation management (Jeronimo de Burgos and Jose 2001). Some improvement actions can be conducted at this stage and many improvements can be gained on, say, product energy consumption and raw materials.

In practice environmental indicators related to design and development such as energy consumption, reprocessed materials, and solid waste influence environmental performance. Also the improvement on these indicators possibly has a great impact on other quality performance such as manufacturing cost, delivery time and product defect. Some researchers pointed out that there is a positive correlation between environmental performance and business performance (King and Lenox 2001; Klassen and McLaughlin 1996; Konar and Cohen 2001). The authors indicated that the achievement on environmental performance can lead to the achievement on financial performance. In other words businesses with less pollution have a greater financial performance. As an environmental policy, the whole concept of environmental performance evaluation and its process have to be considered and performed in the whole production process, and not just in the managerial level. This can be achieved by integrating the customer and environmental requirements at the first step of product design and development process. This evaluation must be part of a continuous improvement project by setting the indicators as an improvement target.

Based on ISO 14032 (1998) there are many benefits which can be achieved by a company by undertaking this evaluation and are summarised into the following factors:

- Clearly understand the impact on the environment.
- Improve the environment.
- To make sure goals, targets and objectives are met.
- Improve organisational efficiency and profitability.
- Achieve and demonstrate compliance with regulation.
- Basis for benchmarking.
- Improve community and customer relations.
- Can determine proper allocation of resources.
- Help with cost/expense management.
- Basis for continuous improvement.
- Trace degree of implementation of EMS.
- Help identify the base problem or root cause.
- Raise environmental awareness within organisation.
- Support environmentally labelling programs.
- Basis for rewarding employees.

Finally, to address environmental impact of an organisation, it has become clear that the development of environmental performance evaluation has to commence with internal aspects of an organisation and link them to its external aspects via setting the environmental evaluation as the first step of product design and development processes, and this evaluation must support the continuous improvement project.

2.4 QFD in the concept of environmentally conscious design

The concept of environmentally conscious design refers to the design approach to produce a product minimise with minimum environmental impact across the product life cycle. This concept will cover any design activities related to improving the environmental performance of a product (Hauschild, Jeswiet and Alting 2004a). This concept emphasises the need for consideration of environmental impacts during the product life cycle which involves material extraction, material processing, manufacturing, distribution, use and end of life (Haihong *et al*. 2010). It is important to introduce and integrate environmental aspects into the product design and development process as this

is a critical determinant of a manufacturer's competitiveness. The costs of product development has been claimed to be around 80% of a product's environmental and economic costs (Argument, Lettice and Bhamra 1998; Mascle and Zhao 2008). The need for an approach capable of offering efficiency and being environmentally conscious has become a crucial issue in a successful design process. The growing interest in sustainable development has led many companies to deal with environmental issues by conducting environmentally conscious design (eco-design) or Design for environment (DfE) which considers a potential environmental impact throughout the life cycle of the product (Bevilacqua, M., Ciarapica and Giacchetta 2007). Furthermore this concept also considers design performance with respect to environmental, health and safety objectives along the product life cycle (Mascle and Zhao 2008).

2.4.1 QFD method for environmental consideration

Several methods and tools have been developed and conducted to support the development of DfE. Many researchers have used a concept of QFD and LCA to develop an environmentally conscious design. Some methods and approaches have been verified through several studies incorporating the environmental issues.

Cristofari, Desmukh and Wang (1996) presented green quality function deployment (GQFD) that considered quality requirements, environmental impact and production costs at the design stage. This method was divided into three main phases namely: concept product planning phase, design phase and decision making phase as depicted in Figure 2.14. This method can detect the best product alternative during the design phase and assess the impact of the design choice during its entire life cycle. The method provides a transparent procedure for the life cycle impact assessment and improvement analysis, thereby eliminating the most important limitation of commonly used impact indices. The main aim of this method is to evaluate customer's needs, to identify relationship between customer's needs and Product Technical Requirements (PTR), to set goal values for PTRs and to evaluate the importance of each PTR related to the client's choices, company's strategy and benchmarking against competitors. Matrix of parts (MP) is the foundation of green quality house (GQH) with the main aim of dividing a product into different sub-components and also to determine the relationship between these sub-components and PTRs. The construction of green house (GH) is similar to GQH with the main aim is to

report the correlation between the environmental impacts of the product during production and disposal phase.

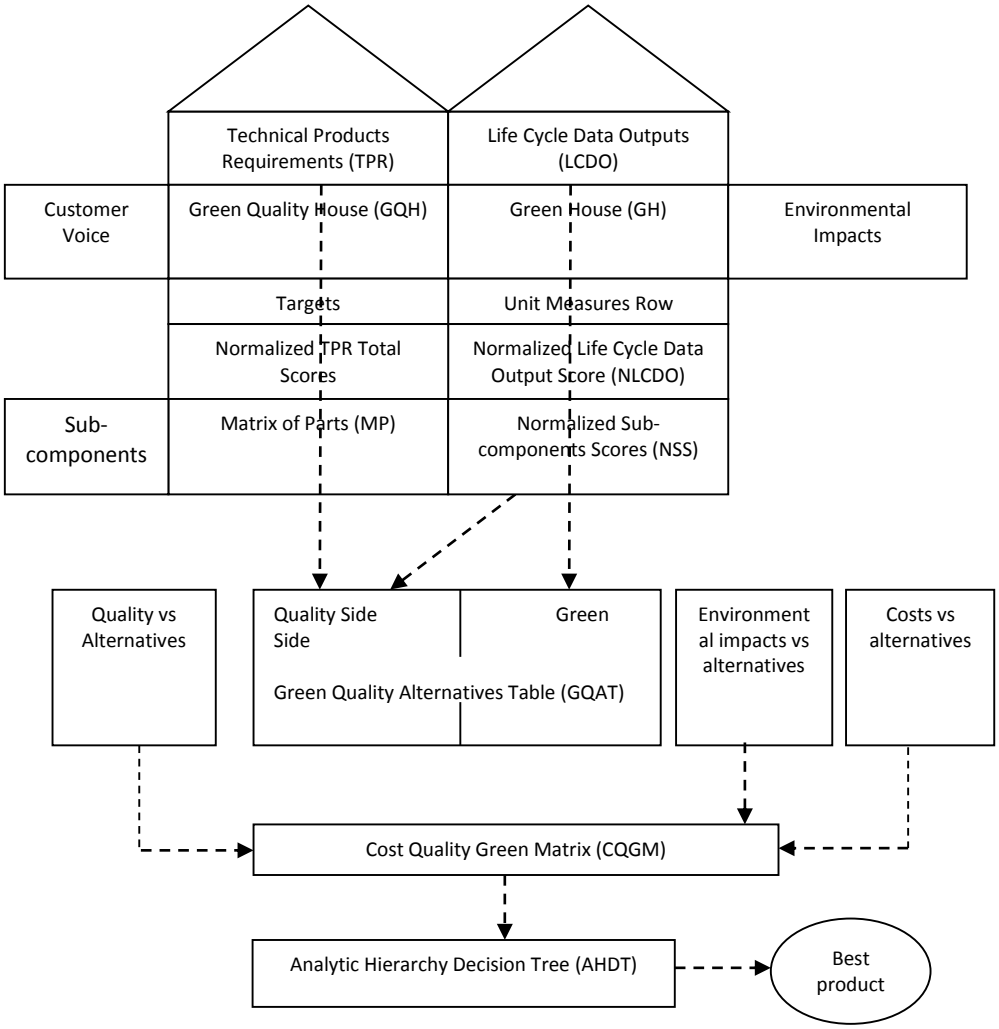


Figure 2.14 Green Quality Function flow chart (adapted from Cristofari, Deshmukh and Wang 1996)

Other researchers developed Green QFD II which integrated life cycle costing (LCC) into QFD matrices and then deployed quality, environmental, and cost requirements throughout the entire product development process (Zhang, Wang and Zhang 1999). GQFD II consists of three major steps namely: technical requirements identification, product concept generation, and product or process design, as depicted in Figure 2.15. In this study the authors pointed out that environmental and cost requirements were established, then quality house, green house, and cost house were constructed in phase I and then followed by generating a series of product concepts to satisfy the established requirements. These concepts can be evaluated and associated to quality, environment,

and cost before the best concept is selected. Finally, in the last phase all requirements from previous phases were deployed into all products/processes to determine a series of matrices including design deployment, process planning, production planning maintenance, and retirement planning. The authors argued that this approach is an efficient tool for product design and development by improving quality, reducing cost and also minimising environmental impacts.

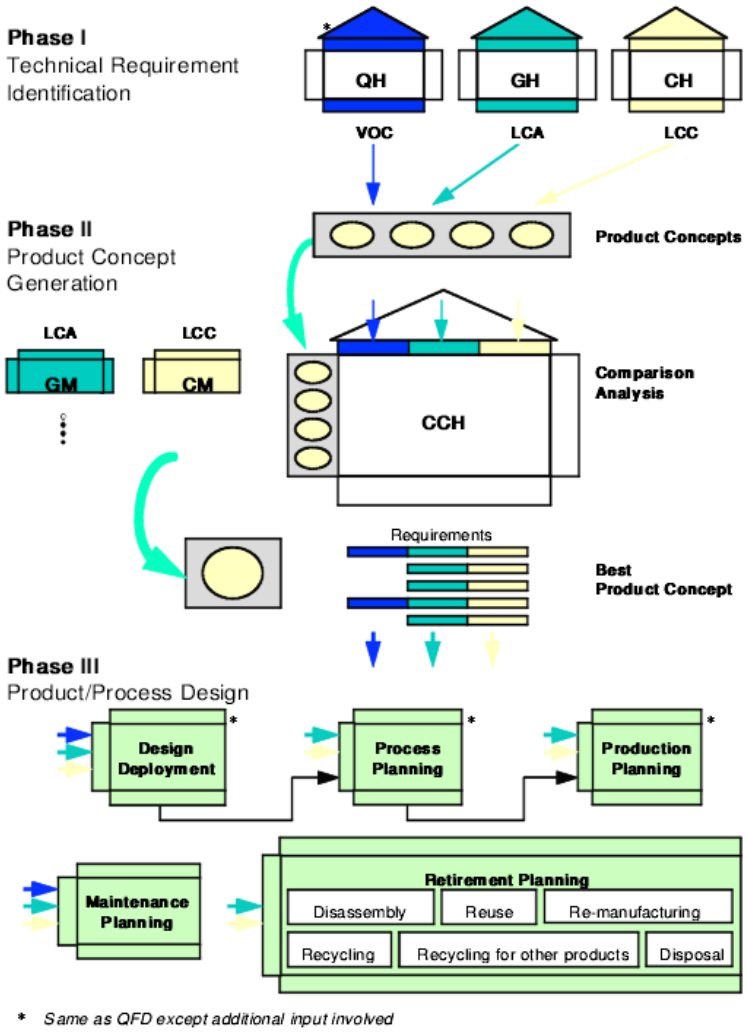


Figure 2.15 The flow chart of GQDF-II (Zhang, Wang and Zhang 1999)

The concept of QFD for environmentally conscious design was developed by (Keijiro *et al.* 2003) who employed the concept of design for environment (DfE) is to develop the methodology as depicted in Figure 2.16. Also environmental aspects were integrated into QFD by developing environmental requirements and engineering metrics to address both environment and traditional product requirements integrally. The authors investigated the

requirements and attributes of environmental concern through a whole product life cycle concept and then converted them into a set of environment voice of customer (VOC) and engineering metric (EM). The proposed method would assist the design team in determining the parts significantly influencing the enhancement of environmental consciousness of their products by executing QFD phase I and phase II. Also the authors developed a methodology to evaluate the effects of design improvement on environmental quality requirements as phases III and IV.

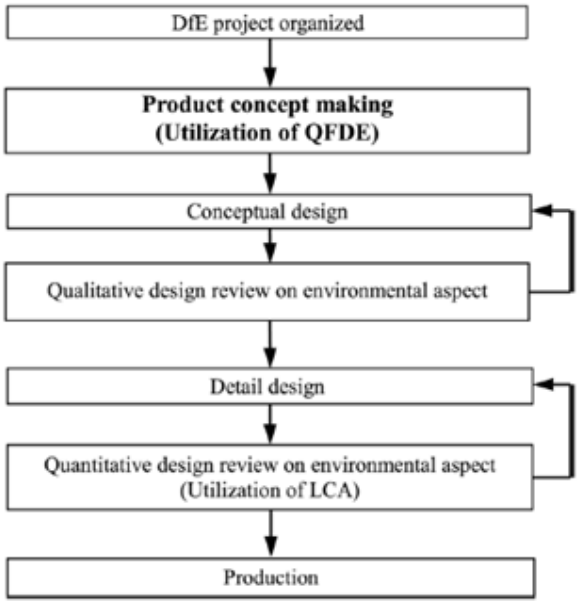


Figure 2.16 The DfE flow (Keijiro *et al.* 2003)

Kaebernick, Kara and Sun (2003) presented some tools for the product development process. The authors presented the methodologies for sustainable manufacturing along with product lifecycle as depicted in Figure 2.17. Environmental requirements can be determined at any development stage by applying customer requirements (CR) and LCA. Then the authors used the concept of QFD to transfer CR into technical and design requirements. The authors proposed a new concept of ECQFD is which covers environmental aspects in the form of environmental metrics (EM) as depicted in Figure 2.18.

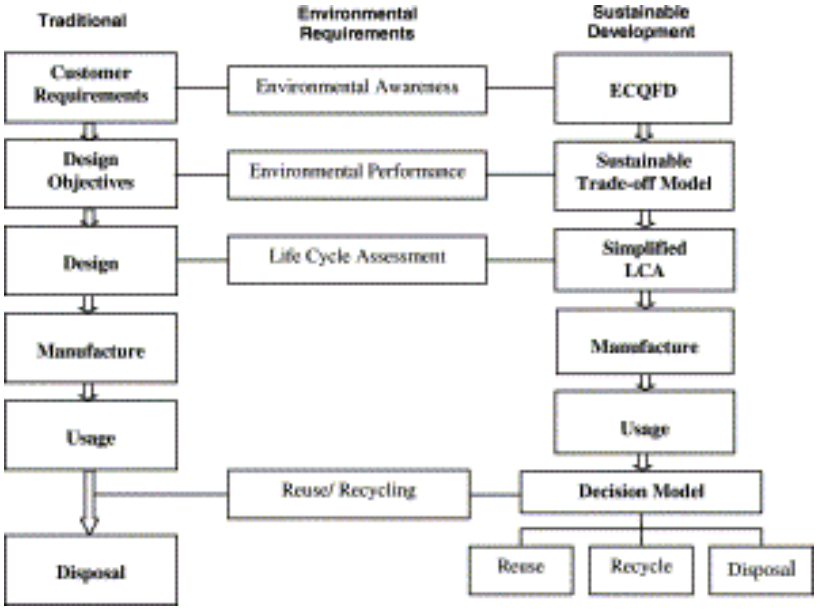


Figure 2.17 Methodologies for sustainable manufacturing at stages of product lifecycle (Kaebernick, Kara and Sun 2003)

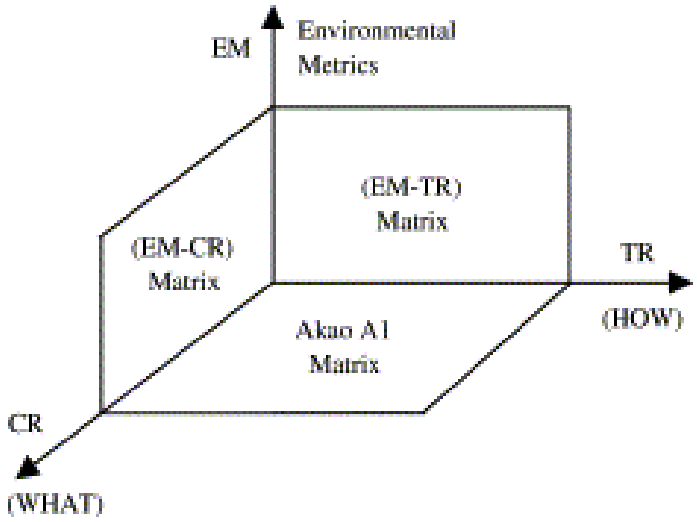


Figure 2.18 Three dimensional ECQFD (Kaebernick, Kara and Sun 2003)

Sakao (2007) proposed a QFD-centred design methodology that involved the integration of three main tools namely: life cycle assessment (LCA), quality function deployment for environment (QFDE) and theory of inventive problem solving (TRIZ) with the main aim of supporting the environmental design of a product. The author pointed out there are three main consideration related to the analysis of an eco-design product. Firstly, it is important to analyse a design by collecting the information on environmental impact of the products and considering the whole life cycle of a product from various environmental

aspects and the concept of ISO-LCA can be used to fulfil this. Secondly, the problem definition needs to be deployed into four major aspects of product development namely: quality, cost, time and environment and the concept of QFDE can be used to meet the requirements. Third, solution identification not only to address environmental requirements but also improving the performance while keeping an existing mechanism. TRIZ method can support the expert team in a company to find improvement solutions. The proposed approach is illustrated in Figure 2.19.

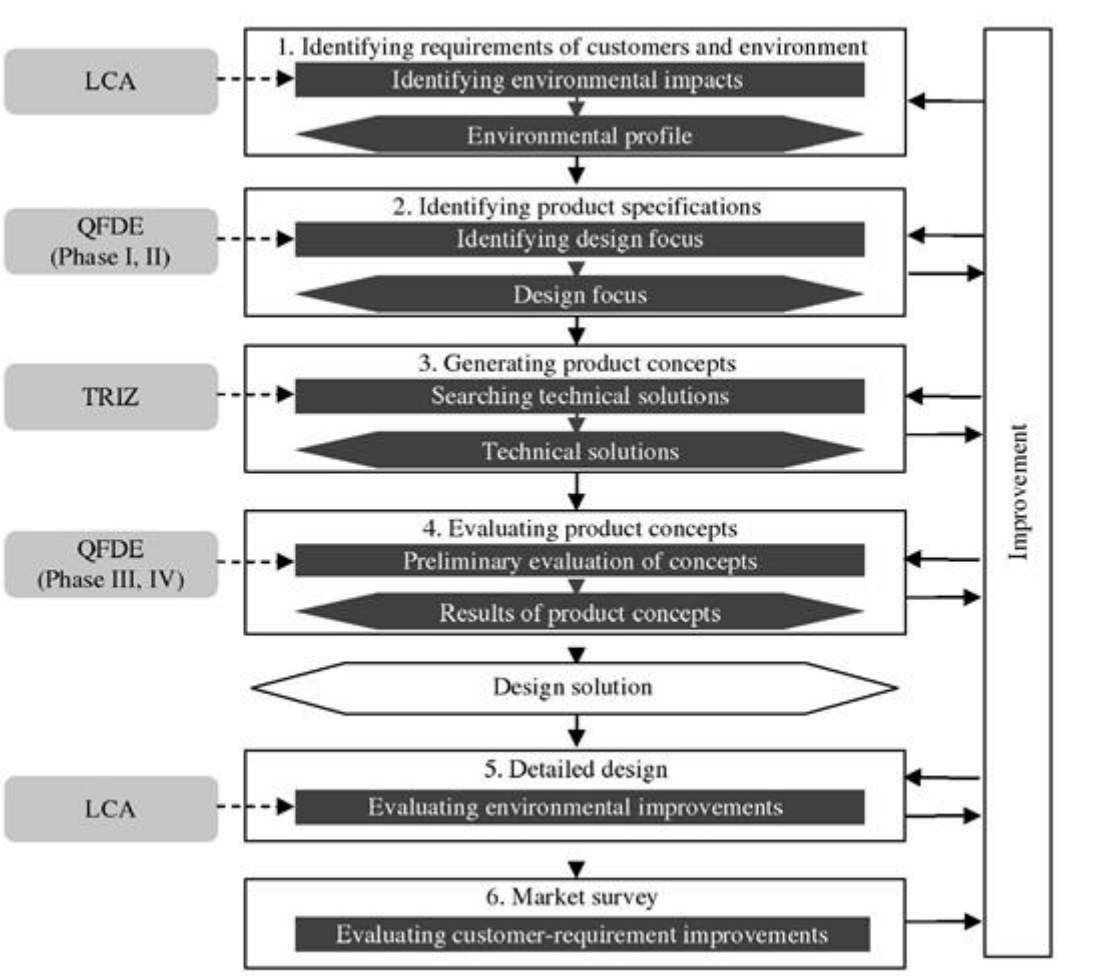


Figure 2.19 Procedures of the eco-design methodology (Sakao 2007)

Cagno and Trucco (2007) used matrix approach as a simplified LCA to integrate green and QFD, called enhanced QFD. Integrated green QFD (IGQDF) is divided into six parts namely: configuration analysis, identification of the customer's extended quality needs, structuring of the project and product specifications, green and quality house (GQH), choice of concept, and development of product features and design matrix as depicted in Figure 2.20. The structure of the green and quality house are depicted in Figure 2.21.

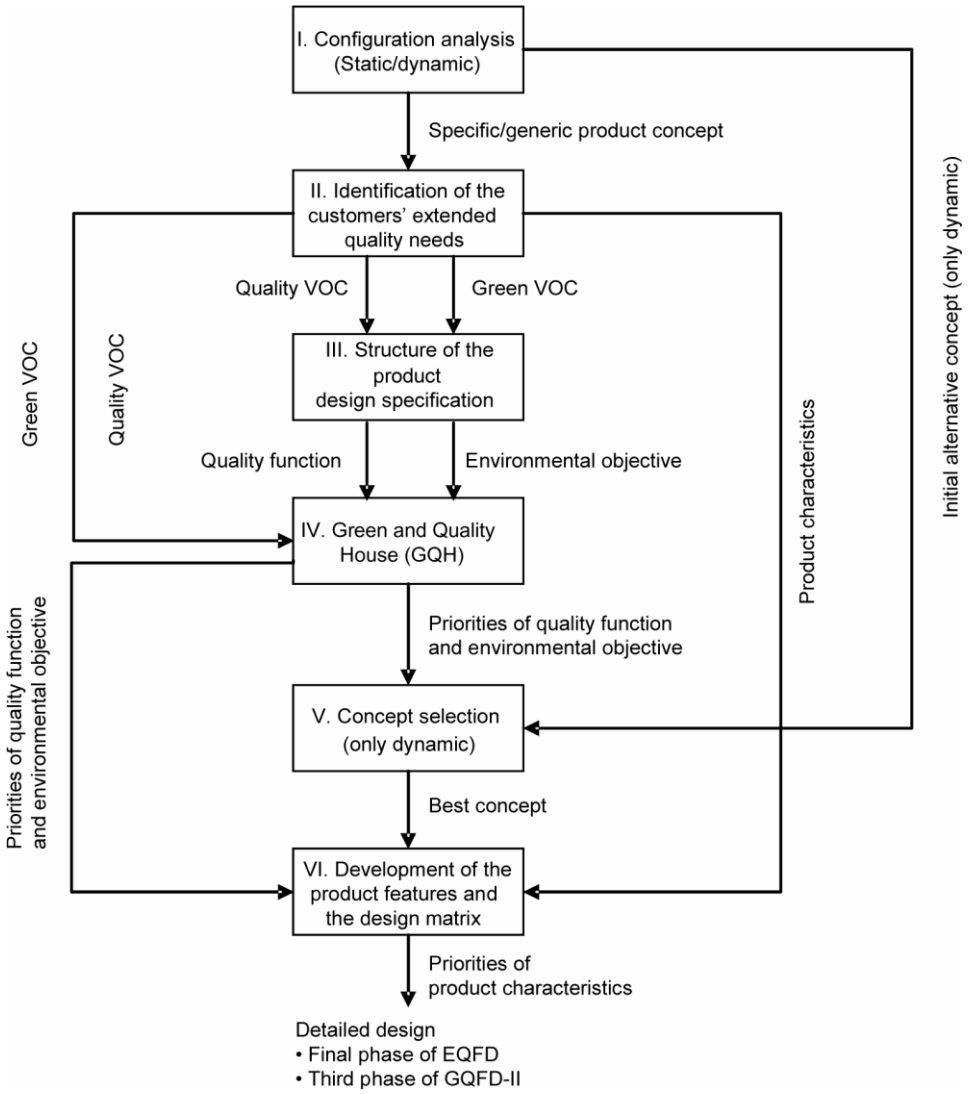


Figure 2.20 Sequence of the phases of the integrated green and quality function deployment (Cagno and Trucco, 2007)

Kuo, Wu and Shieh (2009) developed Eco-quality function deployment (Eco-QFD) in order to accommodate environmental considerations to improve customer satisfaction. The authors presented the integration of fuzzy concept into a QFD method to address the vagueness and uncertainty during the decision making process and highlighted that the fuzzy multi-objective model considers overall customer satisfaction and encourages industry to produce environmentally friendly products. QFDE is carried out through four phases as illustrated in Figure 2.22 where phase I and II will allow the user to identify environmentally significant components of the product, and phase II and IV will allow the user to choose the most environmentally friendly design from alternative design proposal. The framework of HOQ for considering traditional and environmental aspects is depicted in Figure 2.23.

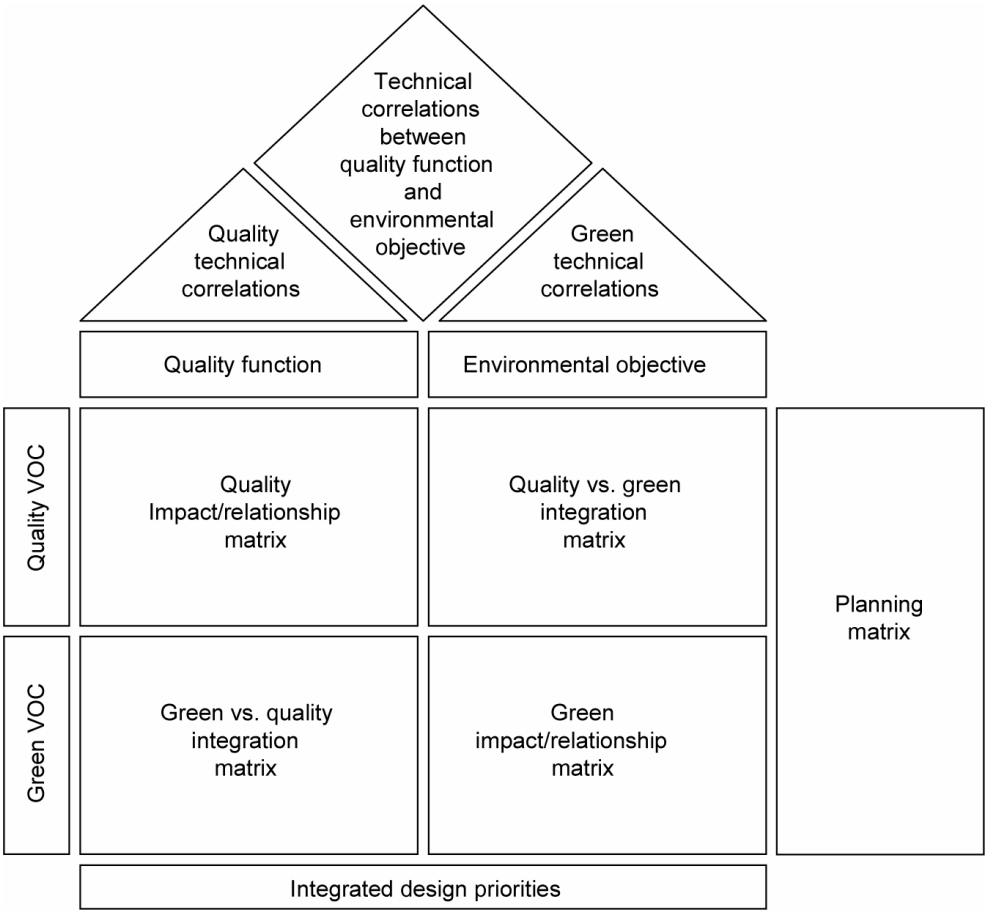


Figure 2.21 Structure of the green and quality house (Cagno and Trucco, 2007)

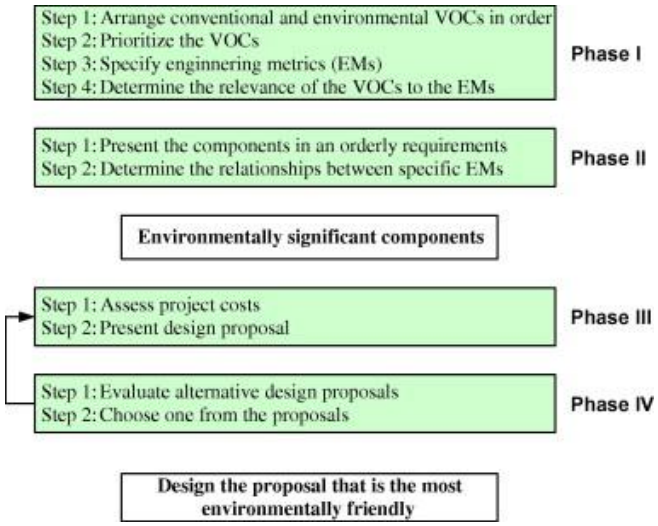


Figure 2.22 Flow of QFDE-based DfE (Kuo, Wu and Shieh, 2009)

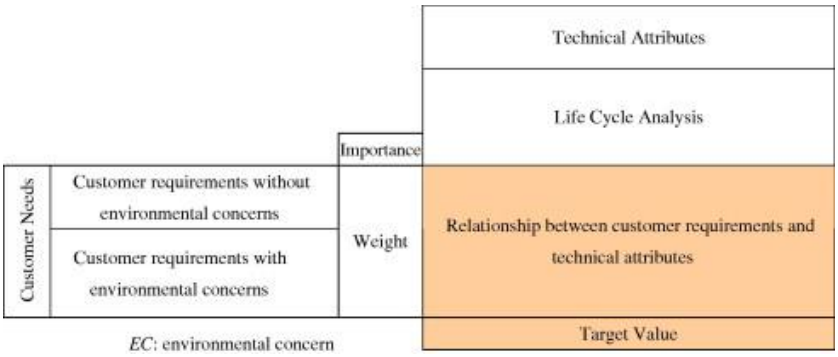


Figure 2.23 The planning of HOQ by further considering environmental concerns (Kuo, Wu and Shieh, 2009)

Bovea and Wang (2007) presented a redesign method for developing environmentally conscious products. The proposed method allows integration of environmental requirements into product development while taking into account cost and customer preferences. The proposed method focuses on establishing the relationship between QFD, LCA, life cycle cost (LCC) and contingent valuation (CV) for evaluating customer, environmental and cost requirements and customer willingness-to-pay (WTP) respectively. The proposed method is structured into a series of matrices as depicted in Figure 2.24 where the importance matrix focuses on targeting product components most important to the customer, followed by an initial environmental/cost matrix that focuses on gathering information related to the current design of products based on the environmental and economic point of view. Then environmental impact/cost and the environmental/cost index can be calculated.

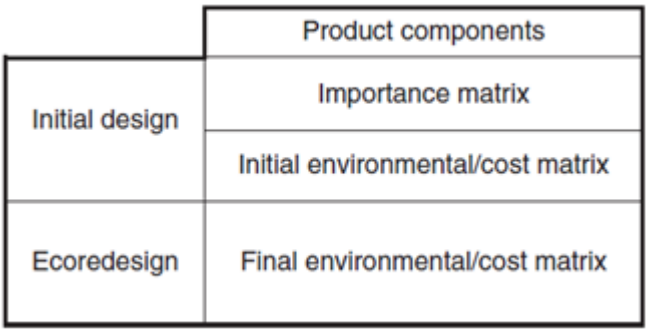


Figure 2.24 Eco redesign methodology (Bovea and Wang 2007)

Yongming, Luo and Li (2009) presented the application of QFD for environmental product eco-design and pointed out that this approach can be used to assist the design team in a company to identify part characteristics and their processes necessary to

improve the product design to get an eco-design scheme. The authors pointed out that the design team in a company can identify the part characteristics that must be considered and then analyse machining process design for environment and product quality control. This QFDE is depicted in Figure 2.25. The authors maintain that the concept of QFDE concerned with process planning and product quality control can lead to customer satisfaction and achieve better market competitiveness.

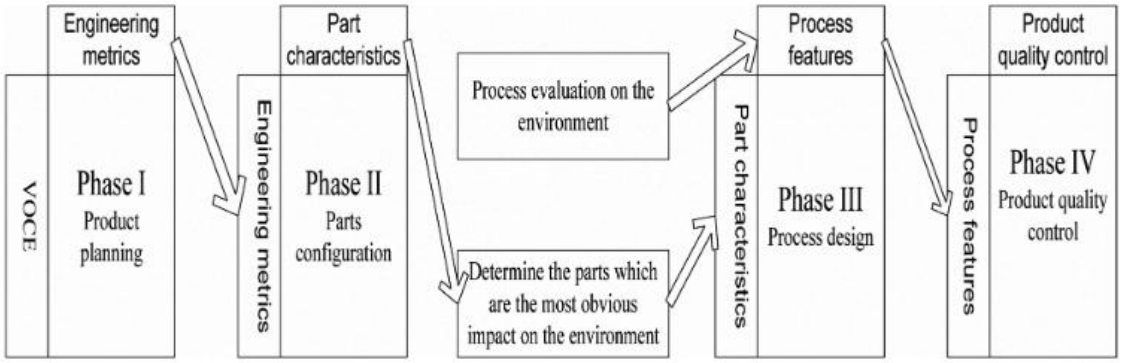


Figure 2.25 The flow of QFDE (Yongming, Luo and Li 2009)

The concept of failure mode effect analysis (FMEA) has also been used to support the design of eco-friendly products. The basic concept of this approach is to identify potential failures in achieving the targeted functions of a process or a new design. The integration of environmental consideration into this concept (E-FMEA) is a promising new tool for DfE where the main aim is to identify and evaluate environmental impacts in all lifecycles phases of a product (Lindahl 1999).

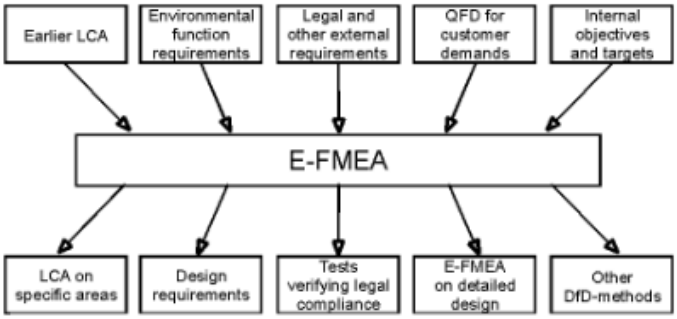


Figure 2.26 E-FMEA (Lindahl 1999)

The author believes this method can take corrective and preventive actions to minimise the environmental burden. To accomplish an E-FMEA some inputs are needed which are sorted, reformulated and analysed as depicted in Figure 2.26. E-FMEA consists of five

main steps namely: identify the product/process lifecycle phase along with all activities related to the phase, identify environmental aspects, find out environmental impacts, evaluate environmental aspects and recommend actions or solutions.

Bovea and Pérez-Belis (2012) reviewed and classified tools that have been developed to evaluate the environmental requirements of products and facilitated its integration into the product design process. The authors classified the tools integrating environmental requirements into the product design process as illustrated in Figure 2.27.

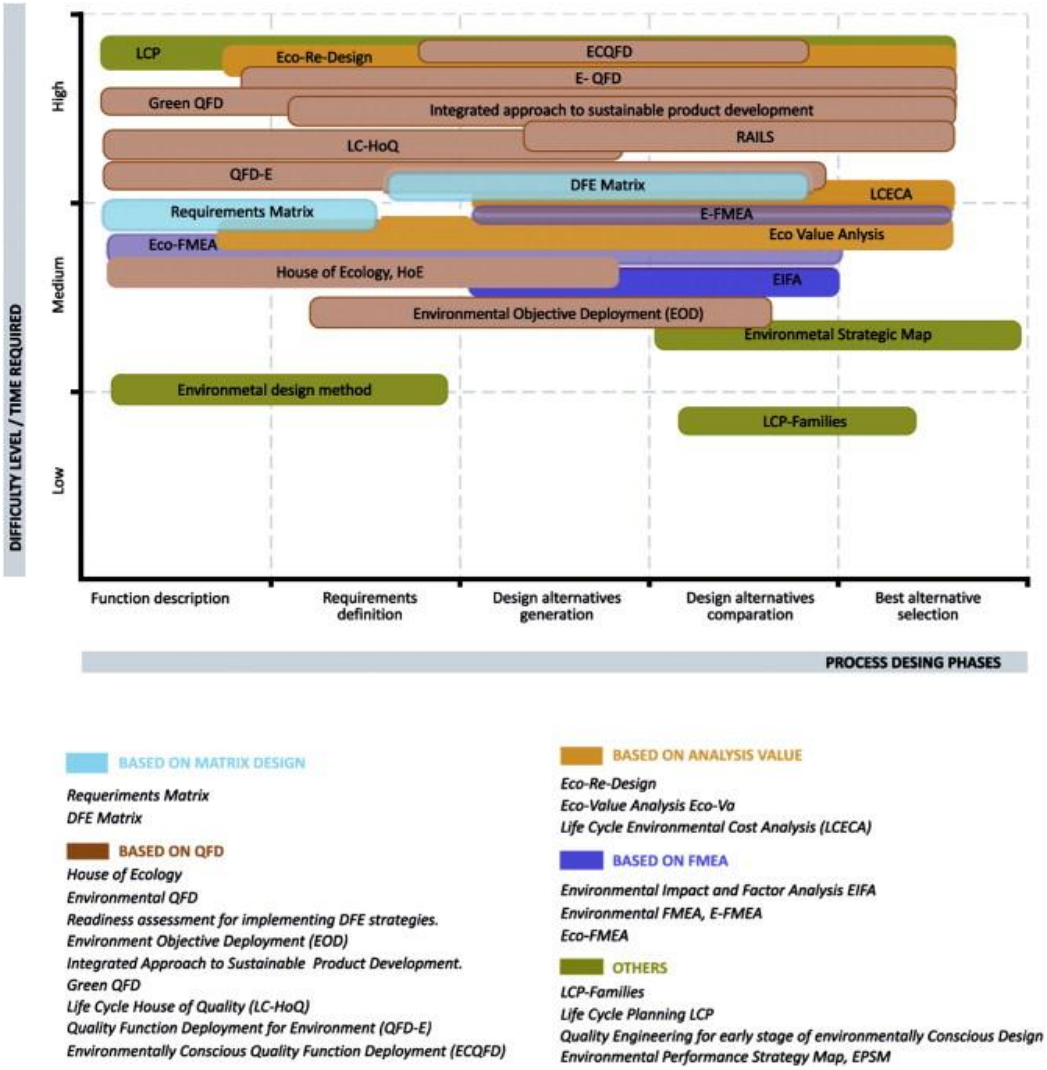


Figure 2.27 Classification of tools integrating environmental requirements into the design process (Bovea and Pérez-Belis 2012)

The authors pointed out that there are two main consideration related to a taxonomy of the eco-design tools. Firstly, an overview of existing techniques for evaluating the environmental requirements of products and secondly, the review of eco-design tools developed for incorporating environmental requirements into the product design and development process. There are three key factors involved in the optimisation of the process of product eco-design namely: early integration of environmental aspects into the product and development process, life cycle approach to determine the impact of the product on the environment in different stages, and a multi-criteria approach integrating all traditional requirements, environmental aspects and their impacts.

Bovea and Vidal (2004) proposed an eco-design model by integration of three methods, namely LCA, LCC, and contingent valuation (CV) to evaluate environmental requirements, examine the internal and external cost of the products and to quantify the customer's value which is referred to as willingness-to-pay (WTP). The model is depicted in Figure 2.28. The authors maintain that their model leads to a better environmental behavior, cost estimation, and customer requirements through the customer WTP.

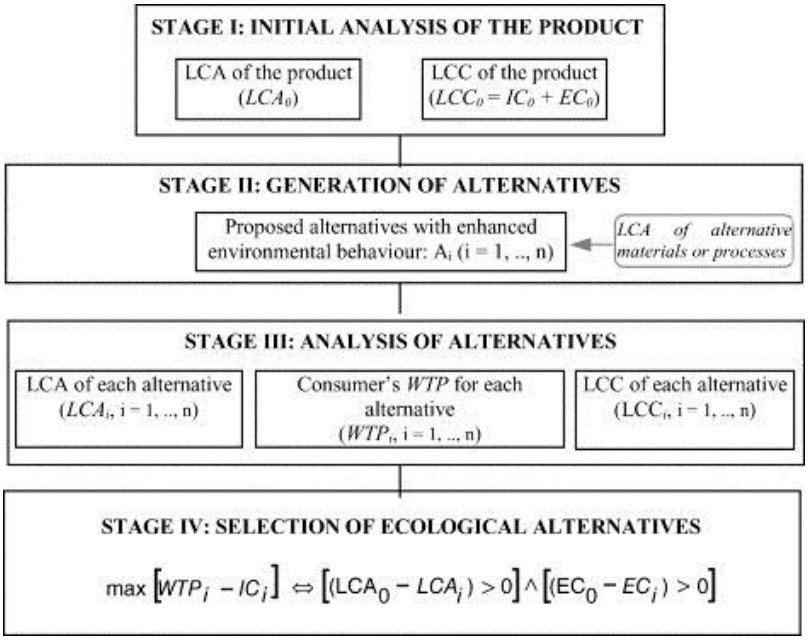


Figure 2.28 Model of eco-design of products (Bovea and Vidal 2004)

Kobayashi (Kobayashi 2006) presented the life cycle planning (LCP) integrated with QFD to address the development of eco-products. Two main concepts have been considered in this approach namely: incorporating environmental aspects into product

design and development processes and also determination of the best mixture of life cycle options at the component level using analytic support. Also the concept of LCP integrated with quality, cost and environmental aspects in the early phases of eco-design is presented to provide a more innovative product eco-design approach and it is depicted in Figure 2.29.

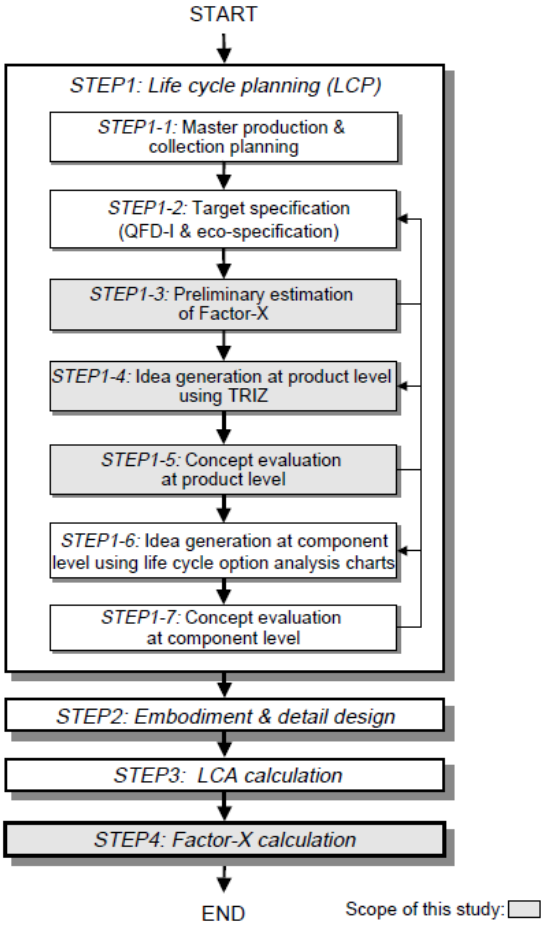


Figure 2.29 Model of eco-design of products (Kobayashi 2006)

2.4.2 The strength of QFD for environmentally conscious design

The concept of QFDE has been verified through several studies and other QFD based methods incorporating the environmental issues have been developed. This indicates that the effectiveness of QFD based methods for designing and creating environmentally friendly products is widely recognised. Therefore QFD can be used to support the development of environmental performance. By integrating this approach into the environmental performance evaluation process it can aid the expert team in a company to identify environmental requirements and indicators within the production process and prioritise them according to the company's circumstances. Then the selected

environmental indicators can be used as input variables for developing an environmental performance evaluation model. Although AHP is another tool widely recognised for determining the priority of environmental impact factors such as greenhouse gases, it has not been employed in this research simply because it does not accommodate environmental requirements, indicators and correlation between these two.

2.5 Research gaps

The extensive review of the current literature in the area of environmental evaluation, in this chapter, has revealed several research gaps as follows:

- Firstly, as previous discussed, environmental indicators can be classified into internal and external indicators. Most of the current studies tend to focus on external indicators, such as emission, and there are very few studies that focused on internal indicators. This is clearly indicated in Table 2.4 (Column c).
- Secondly, there is a lack of integration of environmental performance evaluation into product design and development processes or continuous improvement methodology. This is clearly indicated in Table 2.4 (Column e).
- Thirdly, there is a lack of a systematic approach to be used by organisations to guide them in the selection of environmental indicators and design an environmental performance evaluation to meet their specific goals.
- Fourthly, there is a lack of qualitative and quantitative research focused on designing a model of environmental performance evaluation flexible enough to adopt various indicators and integratable with continuous improvement methods.

2.6 Research ideas

Literature review and research gaps described previously, reveals the need to develop a systematic approach to design a flexible environmental performance evaluation open to modification and applicable for any manufacturing industry. Six research ideas were identified as follows:

- determine environmental requirements related to the design of an environmental performance evaluation model;
- determine appropriate environmental indicators for an organisation;
- integrate environmental requirements and environmental indicators in the product design development process;

- prioritise environmental indicators;
- develop appropriate indicators metrics; and
- develop an approach for designing a model of environmental performance evaluation flexible enough to be further modified and applicable to any manufacturing company.

Table 2.4 Summary of literature on environmental performance evaluation

References (a)	**Tools (b)**	**Area (indicators)**		**Integrated with product design dev. (e)**	**Applicability (f)**
		Internal (c)	**External (d)**		
Corbett and Pan (2002)	statistic tools	-	√	-	generic
Rao *et al.* (2006)	statistic tools	-	√	-	SMEs
Seroa da Motta (2006)	linear model	-	√	-	generic
Henry and Journeault (2008)	statistic tools	-	√	-	generic
Srebotnjak (2007)	Statistic tools	-	√	-	generic
Diakaki, Grigoroudis and Stabouli (2006)	risk assessment	-	√	-	dairy industry
Dias-Sardinha and Reijnders (2005)	Balance score card	-	√	-	generic
Hsu and Liu (2010)	Balance score card	-	√	-	automobile
Tam, VWY *et al.* (2006)	Questionnaire	-	√	-	generic
Munksgaard *et al.* (2007)	DEA	-	√	-	generic
Bevilacqua, Maurizio and Braglia (2002)	DEA	-	√	-	generic
Kortelainen (2008)	DEA	-	√	-	generic
Zhou, P., Ang and Poh (2006)	DEA	-	√	-	generic
Zhou, Peng, Poh and Ang (2007)	DEA	-	√	-	generic
Färe, R., Grosskopf and Hernandez-Sancho (2004)	DEA	-	√	-	generic

Table 2.4 Summary of literature on environmental performance evaluation (cont.)

References (a)	Tools (b)	Area (indicators)		Integrated with product design dev. (e)	Applicability (f)
		Internal (c)	External (d)		
Färe, Rolf, Grosskopf & Pasurka (2010)	DEA	-	√	-	coal-fired power plant
Jia, Han and Tan (2004)	AHP, MCDM,	-	√	-	chemical process
Vandermulen *et al.* (2003)	LCA	-	√	-	railway business
Ana Claudia *et al.* (2004)	LCA	-	√	-	generic
Pineda-Henson, Culaba and Mendoza (2002)	AHP, LCA	-	√	-	pulp and paper
Montanari (2004)	MCDM	-	√	-	thermo power plant
Tsoulfas and Pappis (2008)	MCDM	-	√	-	generic
Hermann, Kroeze and Jawjit (2007)	LCA	-	√	-	generic
Awasthi, Chauhan and Goyal (2010)	Fuzzy	-	√	-	supplier
Tuzkaya *et al.* (2009)	MCDM, fuzzy	-	√	-	supplier
Büyüközkan and Çifçi (2012)	MCDM, fuzzy	-	√	-	supplier
Nasiri and Huang (2008)	Fuzzy	-	√	-	waste recycling program
Barbiroli and Raggi (2003)	quantitative method	-	√	-	generic
Siracusa, La Rosa and Sterlini (2004)	env.protection index	-	√	-	polymer industry
Brent and Visser (2005)	EPRII	-	√	-	generic

Table 2.4 Summary of literature on environmental performance evaluation (cont.)

References (a)	Tools (b)	Area (indicators)		Integrated with product design dev. (e)	Applicability (f)
		Internal (c)	External (d)		
Peroto *et al.* (2008)	environmental analysis	-	√	-	generic
Tam, CM, Tam and Tsui (2004)	MCDM	-	√	-	construction
Tam, VWY *et al.* (2006)	EPA	-	√	-	construction
Yao *et al.* (2007)	fuzzy	-	√	-	construction
Shen, L-Y *et al.* (2005)	computer based scoring	-	√	-	supplier
Utne (2009)	QFD, LCC, LCA	-	√	√	fishing fleet
Yang, M *et al.* (2011)	QFD	-	√	√	generic
Halog, Schultmann and Rentz (2001)	QFD	-	√	-	generic

2.7 Research objectives

As a consequence of the critical literature carried out in this chapter the main objective of this research is set to design an effective approach to develop a model of environmental performance evaluation flexible enough to be incorporated with other continuous improvement schemes for sustainable product development and meet environmental business goals. The proposed model can be applied by the expert team of industry in a practical way to optimise environmental performance evaluation and attain environmental strategic objectives. A further objective of this research is to incorporate the developed environmental performance model with other quality indicators to support continuous improvement effort. The proposed model needs to account for the variety of environmental indicators for the environmental performance evaluation process and also determine appropriate internal metrics for these indicators. To address the research ideas above, the research objectives in this research are:

- Set and establish environmental requirements and appropriate environmental indicators at the first step of the product design development process for the environmental performance evaluation.
- Prioritise environmental indicators.
- Develop appropriate indicator metrics.
- Design a flexible and modifiable model for environmental performance evaluation applicable to any manufacturing company.

2.8 Concluding remarks

The literature review in this chapter describes the concept of environmental performance indicators and evaluation, and also the concept of conscious product design. The environmental indicators and evaluation were reviewed in details. The lack of consideration internal environmental indicators, from the environmental performance evaluation point of view, was revealed. The strength of the QFD approach for environmentally conscious design was highlighted. Hence the research gap, research ideas, and research objectives were identified.

Chapter Three

Research Methodology and Tools for Modelling of Environmental Performance Evaluation



3.1 Introduction

This chapter presents the research methodology of this research along with the tools and approaches employed herein for modelling the environmental performance evaluation.

3.2 Research methodology

This research is to address the deficiencies of current approaches to environmental performance evaluation and furnish a practical solution via quantitative modelling for the environmental performance evaluation. This aim will be fulfilled by identifying environmental indicators and metrics and incorporating the model into the product design and development processes. The methodology incorporates the entire process from conceptualisation of the problem, development of the model, solving the model, and its application to a case study to validate the model. These four phases are depicted in Figure 3.1 followed by their description in the following sections.

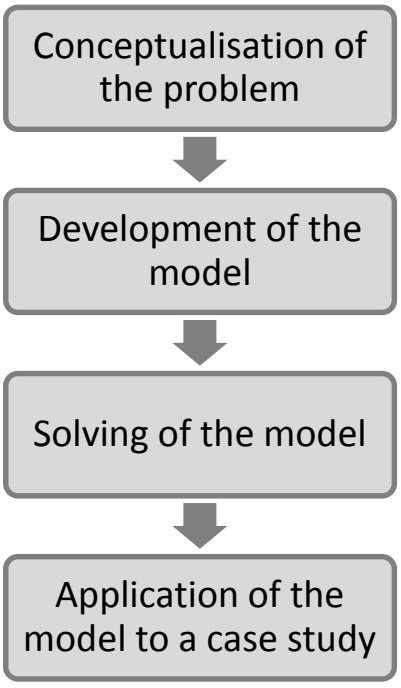


Figure 3.1 The structure of research methodology

3.2.1 Conceptualisation of the problem

The problem of the environmental performance evaluation (EPE) was evolved and developed by undertaking a literature review of the current EPE and its integration into

product design and development processes to meet the environmental requirements and goals of manufacturing companies.

3.2.2 Development of the model

In literature, environmental performance evaluation has been defined as an internal process of management activities of an organisation to measure environmental performance indicators and compare them with environmental criteria set by the management of the organisation. There are two main considerations in developing a systematic approach to environmental performance evaluation. Firstly, how integrating it into the product design and development processes and secondly set it as an improvement target of management strategies where the main aim is meeting the business environmental goals to achieve overall organisational competitiveness. The theory of six sigma and DFSS integrated with QFD (Pusporini, Abhary and Luong 2013a, 2013d) will be used to determine the most significant environmental indicators that influence environmental performance. Six sigma is a process improvement methodology that focuses on customer requirements with the main aim of zero quality defects. The algorithm of design for six sigma (DFSS) with IDOV (*identify, design, optimise* and *validate*) under the six sigma concept will be employed to develop the environmental performance evaluation model.

3.2.3 Solving the model

After the proposed model is developed, a transfer algorithm wil be chosen to represent the system behaviour of the model. The transfer algorithm represents the relationship between multi-input and single-output variables. Then fuzzy inference system (FIS) via MATLAB fuzzy logic tool box will be employed to refine the transfer algorithm of input and output variables. The use of fuzzy logic is because it can account for linguistic and qualitative measures and accommodate multiple variables. Taguchi method will be conducted to determine the contribution of the main environmental indicators on environmental performance (Pusporini, Abhary and Luong 2013c, 2013b).

3.2.4 Application of the model into a case study

The proposed model will be validated via a case study, namely manufacturing company X (name censored due to confidentiality) for which a survey and semi-structured questionnaires were conducted as it is a qualitative method of inquiry that combines a

pre-determined set of open questions (questions that prompt discussion) with the opportunity for the interviewer to explore particular themes or responses further (Clifford, French and Valentine 2010). It also allows respondents to discuss and raise issues that may not have considered and is shown in Appendix 1. These approaches involve experts from the company who have knowledge, skills and experience related to environmental performance evaluation, to collect necessary information. Initially a survey was conducted with functional managers to analyse the current situation of performance measurement and environmental practices in the company and to determine who should be in the expert team to implement the developed model. The current situation of environmental measurement and indicator metrics related to the environmental performance evaluation and management goals were identified through these survey questions. Data was collected from documents, historical charts and observation of processes on the shop floor and used in a case study (Chapter 6) to validate the model.

The selection of tools and approaches for modelling the environmental performance evaluation are explained in the following section.

3.3 Tools selection for modelling of environmental performance evaluation

As described in Chapter 2, environmental performance evaluation has been applied at later stages of the product design and development processes and also was not integrated with any development activities. To address these deficiencies the design of an environmental performance evaluation needs to:

- support the continuous improvement and product design and development processes to meet customer and environmental requirements;
- accommodate varieties of environmental performance indicators;
- select the most appropriate environmental performance measures and metrics; and
- support the development of a robust design of environmental performance evaluation through evaluating, improving, monitoring and controlling the environmental indicators.

In practice the difficulties arise in selecting appropriate environmental indicators that will meet environmental requirements as there are many categories of these indicators. A systematic approach is needed to design this evaluation and determine appropriate

environmental indicators and its metric that meet the environmental business goals of the company, and to integrate this evaluation into continuous improvement activities.

A systematic approach under six sigma methodology (DFSS with IDOV activities) integrated with fuzzy concept is employed. The main reason for choosing a six sigma approach is because it is a powerful tool to improve quality and reduce product defects and can be applied to improve the existing product/process or to design or redesign a product or process. Also this approach focuses on quality in the first step of the product design and development processes to address the lack of integration of the environmental performance evaluation into product design and development processes, and also supports continuous improvement effort.

The selected tools under the six sigma approach such as quality function deployment (QFD), and Taguchi method are explained herein. Fuzzy logic is employed to quantify the subjective and vague statements during the design of EPE and fuzzy inference system (FIS) is used to refine the transfer algorithm of input and output variables in the environmental performance evaluation model.

3.3.1 Six sigma

Six sigma is derived from the normal distribution used in statistical terminology where sigma (σ) means standard deviation. The normal distribution is usually used to represent modelling of many performance random variables with two parameters namely: the central tendency and variation. Six sigma is defined in both business and statistical terms where, in business terms, it is an improvement strategy to improve profitability, reduce waste, reduce quality costs, and increase effectiveness and efficiency of operations that meet with customer's needs and expectations while statistical terms refers to 3.4 defect per million opportunities (DPMO) (Aboelmaged 2010; Fairbanks 2007; Linderman, Schroeder and Choo 2006; McAdam and Hazlett 2010; Montgomery and Woodall 2008) where sigma is a term used to represent the variation of process average.

Six sigma is a business management methodology to improve product quality by decreasing the variability of manufacturing and business processes (Andrew, Richard and Paul 2008; Paulo Augusto Cauchick and João Marcos 2009). In 1987 Motorola introduced this concept and its focus on eliminating variation of process output (Ng *et al.*

2005). Bendell (2006) stated that six sigma is a strategic company approach that focuses on variation reduction and has a significant contribution not only to the quality of the product but is clearly effective in reducing costs and increasing customer satisfaction. This approach uses a set of statistical tools and scientific methods which leads to quality improvement by reducing defects and achieving business performance (Andrew and Richard 2006; Antony, J., Kumar and Tiwari 2005; Banuelas, Antony and Brace 2005; Firka 2010; Goh 2002; Jiju 2006; Kaushik, P and Khanduja 2008; Kwak and Anbari 2006; Mahesh *et al*. 2005; Schroeder *et al*. 2008; Shah, Chandrasekaran and Linderman 2008; Snee 2004; Su and Chou 2008).

The focus of six sigma is a process improvement to increase performance and decrease performance variation. This improvement will lead to reduction of product defect, improvements in profit, increase employee morale, ensure quality of the product and enhance business excellence. The advantage of six sigma compared to other quality improvement methods is that this approach can be applied not only to improve product quality but also to all business operations by improving key processes. For example, the application of six sigma may help to create a well-designed, highly reliable, cost control system, and project management system. There are two well-known main frameworks for six sigma implementation namely DMAIC and DFSS (Montgomery and Woodall 2008). The DMAIC cycle can be deployed as five stages of the process namely: *define, measure, analyse, improve* and *control* (Banuelas, Antony and Brace 2005; Chen, H-C *et al*. 2013; Chen, J-M and Tsou 2003; Gao and Zhou 2013; Gijo, Scaria and Antony 2011; Jirasukprasert *et al*. 2014; Kaushik, PD 2009; Knowles, Johnson and Warwood 2004; Knowles *et al*. 2005; Kumar, Wolfe and Wolfe 2008; Kumaravadivel and Natarajan 2013) and illustrated in Figure 3.2.

DMADV (*define, measure, analyse, design* and *verify*) also well-known as DFSS (Design for Six Sigma) is a systematic approach to design products, processes and services that will meet customer expectations This algorithm can be applied to design or redesign new products or processess (Aggogeri and Mazzola 2008). DMADV like DMAIC uses a set of statistical tools and techniques, such as QFD, design of experiments, seven quality tools, etc. Anthony (2002) pointed out that using the DFSS reduces time to market products, reducing life cycle costs, improving quality and reliability of products or services, and improving market share and business profitability.

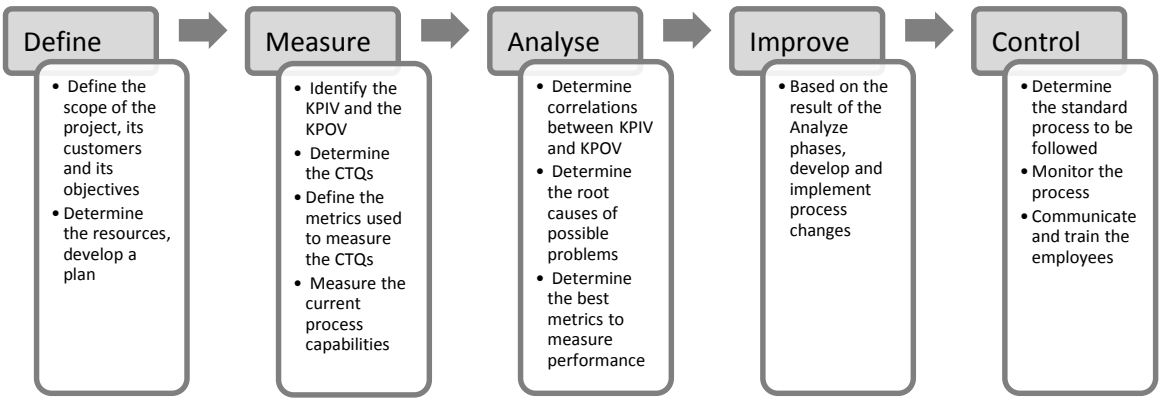


Figure 3.2 The DMAIC process

A common standard of DFSS is IDOV activities (*identify*, *design*, *optimise* and *validate*) analogous to DMADV and illustrated in Figure 3.3. *Identify* as the first stage of IDOV is equivalent with the *define* and *measure* stages of DMADV and *optimise* is equivalent to the *design* of DMADV.

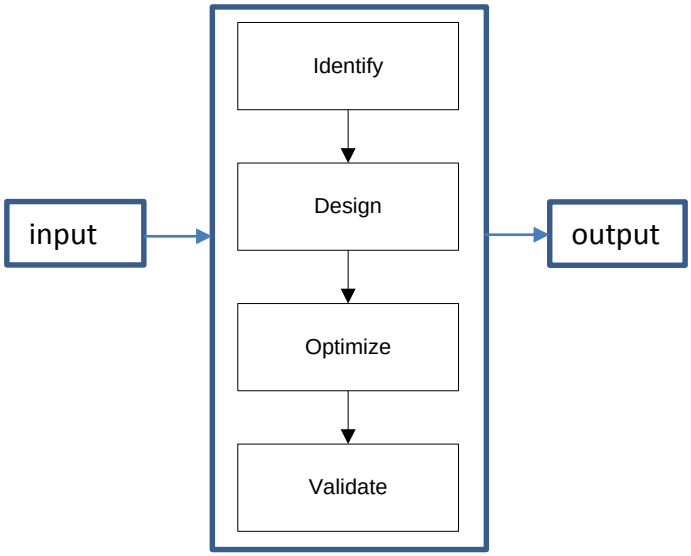


Figure 3.3 DFSS system methodology (adapted from Anthony 2002)

Quality Function Deployment

QFD is a customer-oriented design tool that involves the integration between many cross functions of an organisation like marketing, design engineering, and manufacturing in order to develop and improve the quality of products to enhance customer satisfaction (Karsak 2004). The process of QFD consists of four phases namely: product planning, product design, process planning, and production or process control. The detailed four phases of QFD is illustrated in Figure 3.4.

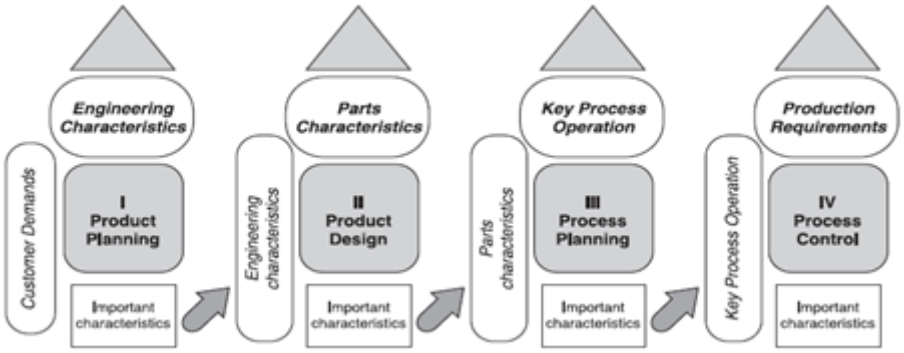


Figure 3.4 The four phases of QFD (Bouchereau and Rowlands 2000)

These four phases of QFD have a similar structure and process with "*whats* and *hows*" in a matrix construction that is called house of quality (HOQ) as depicted in Figure 3.5 which indicates the relationship between customer requirements (what to do) and production requirement or engineering characteristics (how to do it).

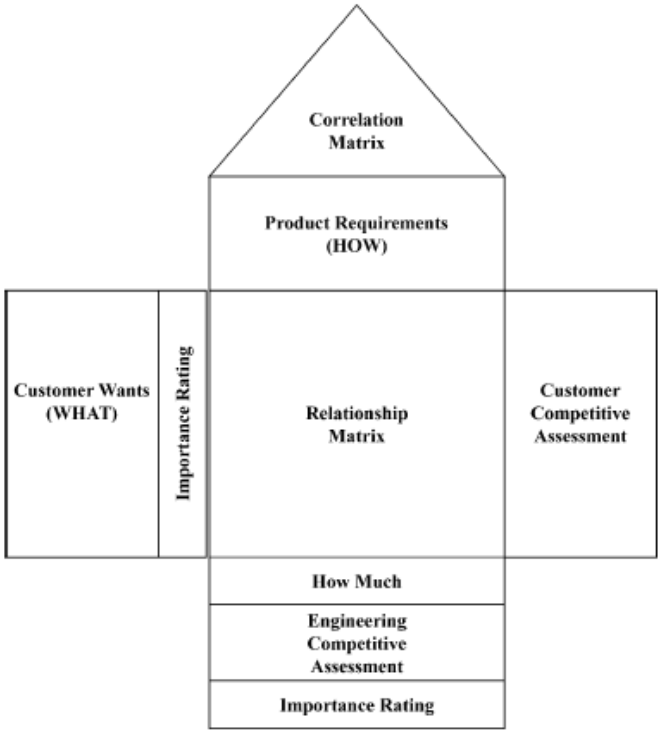
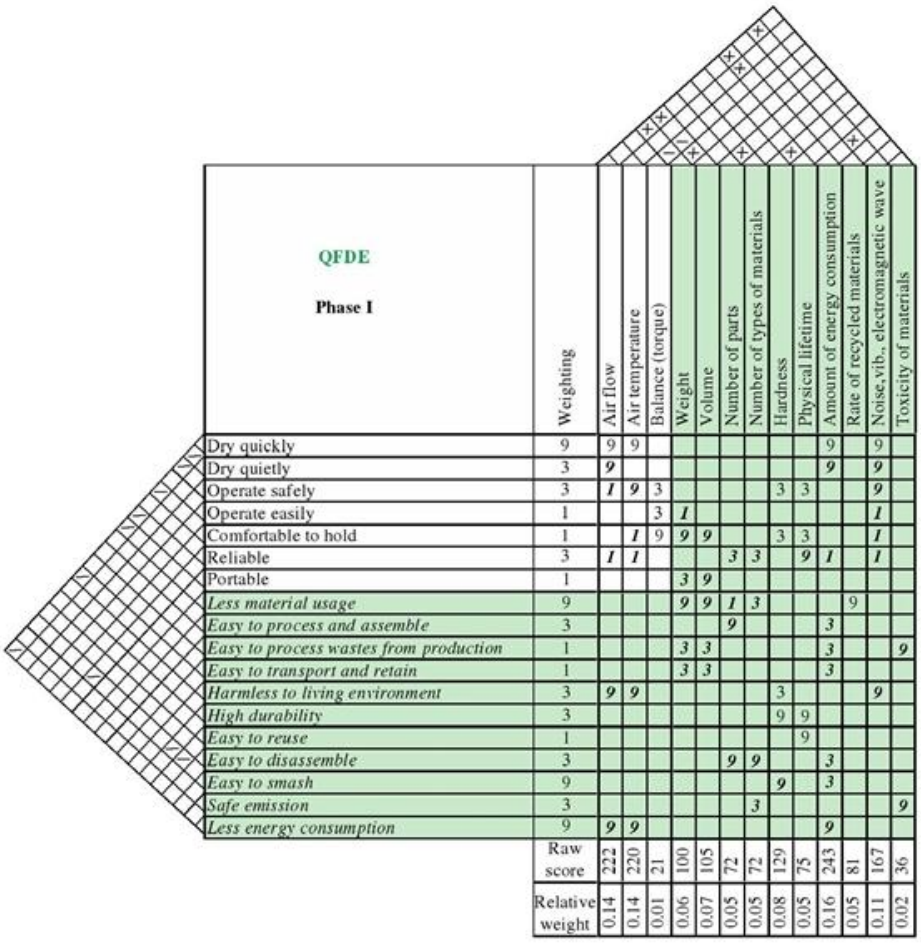


Figure 3.5 House of Quality (HOQ)(Benner *et al.* 2003)

To construct HOQ, expert's judgments will be sought to identify the importance rating for each customer requirement and identify the relationship between customer requirements (*whats*) and engineering characteristics (*hows*). A particular rating scale is usually used for this, for example: the using of rating scale 1 (weak) to 5 (strong) to

identify the relationship between *whats* and *hows*. An example of the application of HOQ is illustrated in Figure 3.6.



QFDE Phase I	Weighting	Air flow	Air temperature	Balance (torque)	Weight	Volume	Number of parts	Number of types of materials	Hardness	Physical lifetime	Amount of energy consumption	Rate of recycled materials	Noise,vib., electromagnetic wave	Toxicity of materials
Dry quickly	9	9	9								9		9	
Dry quietly	3	*9*									*9*		*9*	
Operate safely	3	*1*	*9*	3					3	3			*9*	
Operate easily	1			3	*1*								*1*	
Comfortable to hold	1		*1*	9	*9*	*9*			3	3			*1*	
Reliable	3	*1*	*1*				*3*	*3*		*9*	*1*		*1*	
Portable	1				*3*	*9*								
Less material usage	9				*9*	*9*	*1*	*3*				9		
Easy to process and assemble	3						*9*				*3*			
Easy to process wastes from production	1				*3*	*3*					*3*			*9*
Easy to transport and retain	1				*3*	*3*					*3*			
Harmless to living environment	3	*9*	*9*						3				*9*	
High durability	3								9	9				
Easy to reuse	1									9				
Easy to disassemble	3						*9*	*9*			*3*			
Easy to smash	9								*9*		*3*			
Safe emission	3							*3*						*9*
Less energy consumption	9	*9*	*9*								*9*			
Raw score		222	220	21	100	105	72	72	129	75	243	81	167	36
Relative weight		0.14	0.14	0.01	0.06	0.07	0.05	0.05	0.08	0.05	0.16	0.05	0.11	0.02

Figure 3.6 Example of house of quality (HOQ) (Sakao 2007)

Taguchi method

Taguchi method is used in this research to analyse the main contribution of environmental indicators to environmental performance in the environmental performance evaluation. This approach is based on the fact that the impact of uncontrollable factors can be eliminated by the determination of the level combination of controllable factors or process parameters (Anastasiou 2002; Azadeh *et al*. 2012; Bachlaus, Tiwari and Chan 2009; Dubey 2009; Lu and Antony 2002; Pandey and Dubey 2012; Syrcos 2003; Tan and Tang 2001; Tarng, Yang and Juang 2000; Wang and Huang 2007; Yang, T, Wen and Wang 2011). Environmental indicators as controllable factors in the proposed model can be set and will affect to environmental performance. There are four main steps for the Taguchi experiment namely: selection of quality characteristics, selection parameter design, selection of orthogonal array, and interpretation of experiments result. The quality

characteristic in this research refers to the measurement of environmental performance evaluation that is based on the achievement of an environmental performance value and indicates *a larger-the-better* (LTB) characteristic.

3.3.2 Life cycle of a product

Environmental evaluation should be performed at the design phases of life cycle of product (Figure 3.7). This means that it is much cheaper to design a product for more suitable recycling than to invest in its improvement for recycling at the later stages of the production. This concept will be able to oversee the entire life cycle of a product and using this approach gives the potential to optimise the effects of improvements.

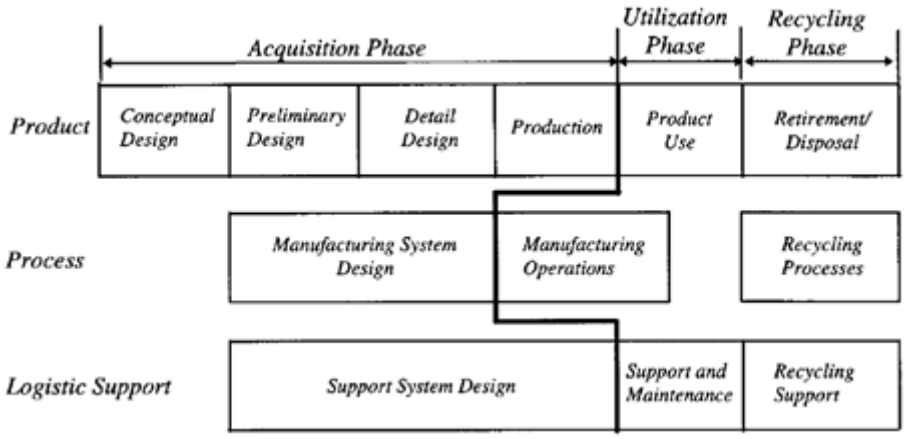


Figure 3.7 Parallel life cycles in product development (Asiedu and Gu 1998)

3.3.3 Fuzzy inference system (FIS)

This research applies fuzzy inference system (FIS) to develop the environmental performance evaluation model. The essential concept of FIS is the fuzzy algorithm which are derived from fuzzy logic (Zadeh 1983). The developing of environmental performance evaluation involves expert judgments, then the fuzzy logic is employed as it was developed based on the exact premise that the key elements in human thinking are not numbers but linguistic terms or labels of fuzzy sets where they relate to imprecision and vagueness (Al-Najjar and Alsyouf 2003; Humphreys *et al*. 2006; Khanlari, Mohammadi and Sohrabi 2008; Tsai-Wai, Lin and Chen 2003). The concept of linguistic variables is very useful to be reasonably described in a conventional quantitative expression. Linguistic variables as variables whose values are words or sentences in natural or artificial language have been developed (Zadeh 1983). The basic structure of a

fuzzy inference system consists of five conceptual components namely: a fuzzifier, a database, a rule base, an inference engine, and a defuzzifier as illustrated in Figure 3.8. A fuzzifier converts real numbers of input into fuzzy sets; a database contains the membership function of fuzzy sets; a rule base contains a set of linguistics statements of the form (if-then rules); an inference engine performs the inference operations on the rules to infer the output; and a defuzzifier converts the fuzzy outputs into a noun fuzzy output real number.

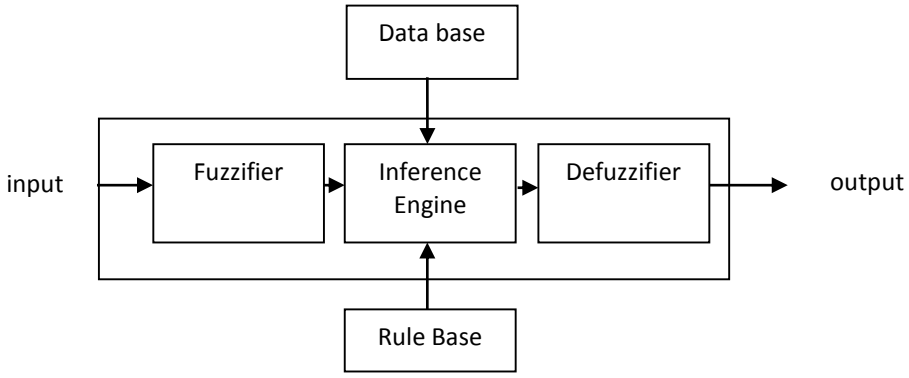


Figure 3.8 The structure of fuzzy expert system

3.3.4 Proposed DFSS strengthened with FIS

This section proposes a DFSS be integrated with an FIS to design a model of environmental performance evaluation. As described previously, there is a lack of current environmental performance evaluation which is integrated into the product design and development process, hence this research focuses on how to design a systematic approach of environmental performance evaluation that is flexible enough to be modified and can adopt varying environmental indicators and support continuous effort. The main reason for choosing DFSS with IDOV activities is based DFSS is a proactive method where the ultimate goal is to "*do the right things and do things right all the time*" (Yang and El-Haik 2003) and also the DFSS is a powerful approach to designing products, processes and services to meet customer requirements and expectations in a cost effective way (Anthony 2002). This research proposed that a DFSS with IDOV (*identify*, *design, optimise* and *validate*) activities is an appropriate tool for designing an environmental performance evaluation model. Then fuzzy logic is integrated in the proposed model because the design of environmental performance evaluation will involve human judgement which is subjective, vague, and imprecise whereby, using a fuzzy concept, can

address this subjective and vagueness and can adopt any qualitative information and provide a greater flexibility by acquiring expert judgments.

Identify

The main purpose of this stage is how to identify and establish environmental requirements (*ER*) and environmental indicators (*EI*). Based on the fact that there are many varieties and categories of *ER* and *EI*, the expert team in the manufacturing industry has to clearly identify the requirements and then prioritise them for environmental satisfaction. A systematic approach is desirable to identify environmental requirements and indicators. A concept of QFD with HOQ will assist the expert team to identify environmental requirements and indicators and also prioritise environmental indicators to provide environmentally friendly products. The use of qualitative assessment in the QFD which are subjective, vague and imprecise will be treated by using fuzzy logic. There are two main advantages of conducting fuzzy QFD at this stage; firstly this framework can integrate environmental requirements and indicators in the first step of product design and development process, and secondly this framework will assist the expert team to determine the significant environmental indicators to be set as a target for continuous improvement.

Design

After having translated environmental requirements the expert team has to identify what environmental performance indicators could be set as appropriate input variables for the proposed model. Based on the fuzzy QFD results in the previous stage, multi input variables and single output variable can be developed. Input variables represent the most significant environmental indicators of the fuzzy QFD result while the output variable represents the environmental performance based on the input variables provided and will be transformed into linguistic terms. Once determined, environmental performance as a function of environmental indicators was introduced as a transfer algorithm. Fuzzy logic also will be proposed to refine the transfer algorithm of input and output variables to suit the environmental performance evaluation.

Optimise

After the proposed design is developed the model can then be optimised. The main function of this step is to optimise the environmental performance evaluation process to

identify the most significant indicators that affect environmental performance as the output variable. The concept of fuzzy logic will be employed and commences with the fuzzy set theory which has been developed for modelling a complex system in an uncertain and imprecise environment. Fuzzy logic refers to the fact that the logic involved can deal with concepts that cannot be expressed as true or false but rather as partially true. One of the biggest advantages of using fuzzy logic rather than other approaches is because this approach appeals to human intuition as they contain linguistic variables, linguistic terms and their experience can be used in the design of the controller. Fuzzy inference system (FIS) is employed in this stage to develop the proposed model. FIS is a framework which stimulates the behaviour of a given system as if-then rules through knowledge of experts or past available data of the system. One main advantage of FIS is because this approach can handle linguistic concepts and contains fuzzy rules built from expert knowledge. The are many advantages of using fuzzy logic in this research:

- the concept of fuzzy logic is easy to understand and flexible;
- this concept has the ability to deal with imprecise and inperfect data or information;
- fuzzy logic can model nonlinier problems;
- fuzzy logic can be built upon the experience of experts;
- fuzzy logic can be blended with conventional control techniques; and
- fuzzy logic is based on natural language.

The fuzzy logic tool box from MATLAB software will be employed to apply the proposed model. There are two types of FIS that can be applied in the MATLAB fuzzy logic tool box namely: Mamdani type and Sugeno type where the difference is on the determined output. In the Mamdani type, the output membership function of output variable is a fuzzy set, while in the Sugeno type a constant value is used as the output membership function. In this research FIS from the Mamdani type is selected to evaluate and aggregate the fuzzy rules as performance or satisfaction levels of an output cannot be judged by discrete values. The Mamdani fuzzy model is proposed to represent the relationship between input and output variables of environmental performance evaluation. This model is based on the collections of if-then rules with both fuzzy antecedent and consequent predicates. Its advantage is that the rule base is generally provided by an expert and hence, to a certain degree, is transparent for interpretation and analysis. The main steps in its design are: selection of input and output variables, determining the range of input and output variables, establishing the membership function for input and output variables,

formulation of the set of linguistic rules to represent the relationship between the system variables, and evaluation of the model. If the proposed model does not produce the desired results then it can be modified through adjusting the rules in the previous stage.

Validate

The main purpose of this final step is to verify, check, monitor and control the processes whether it is complete, valid and also meets practical environmental requirements. To ensure this occurs the proposed model needs to be verified by an application in actual industry as a case study. If the result of the proposed model does not meet environmental requirements then the proposed model needs to be redesigned by returning to an earlier step (design stage) or requires redesign.

3.4 Concluding remarks

This chapter described the research methodology and tools and approaches from six sigma to design an environmental performance evaluation model. DFSS, Fuzzy Logic, QFD, HOQ, and Taguchi Method will be integrated in an algorithm for environmental performance evaluation at an early stage of product design and development processes.

Chapter Four

Approach to Modelling of Environmental Performance Evaluation



4.1 Introduction

This chapter presents the modelling approach for environmental performance evaluation (EPE). To build up the model it is important to determine what the element of the model, the step of modelling, and element of the step in a logical sequence. The modelling approach in this research uses design for six sigma (DFSS) and fuzzy inference system (FIS) (Pusporini, Abhary and Luong 2013a, 2013c). As described in Chapter 2, EPE refers to an internal process of any manufacturing company for measuring environmental indicators and comparing them with the criteria set by the company's management. Environmental indicators are identified as input variables of the model and their influence on the environmental performance as output variables. The detailed description of tools and approaches used to develop the proposed model were provided in Chapter 3. The development of the proposed model in this research will follow IDOV (*identify*, *design*, *optimise*, *validate*) activities from a DFSS cycle as illustrated in Figure 4.1 and explained in this chapter.

4.2 Identify / Quantitative presentation of fuzzy QFD

Refer to Figure 4.1 identify is the first stage of IDOV activities where the main aim is to determine and prioritise environmental requirements and indicators. The QFD approach is employed in this stage.

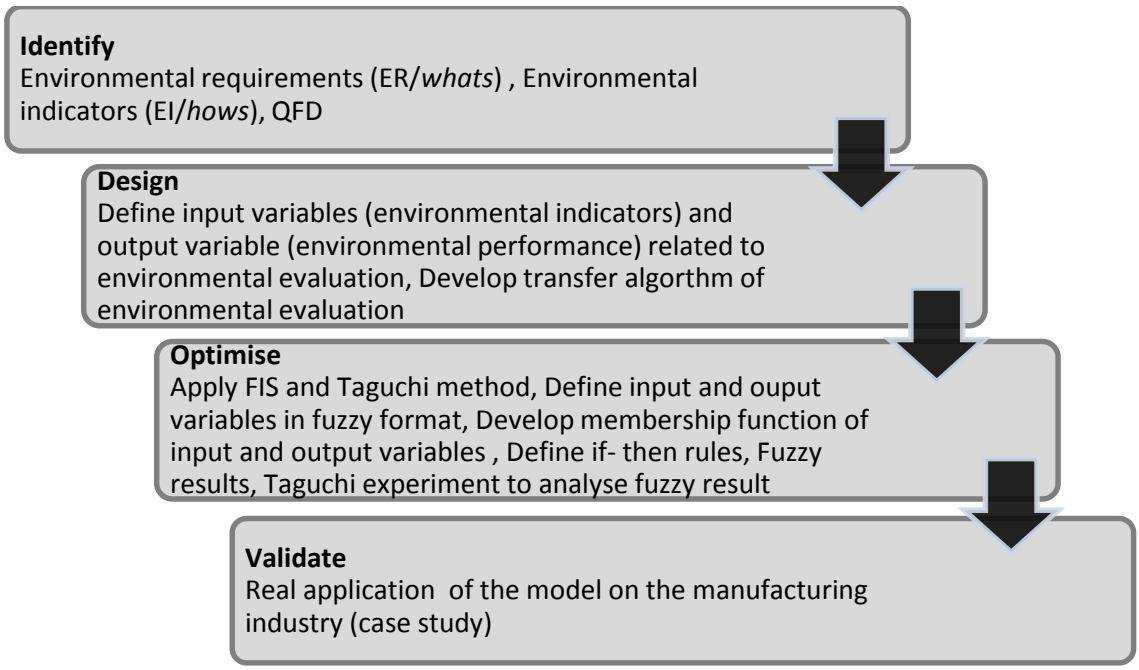


Figure 4.1 DFSS flow for environmental performance evaluation

This stage focuses on environmental aspects including identifying environmental requirements and indicators related to the design of EPE. Pusporini, Abhary and Luong (2011) highlighted the importance of introducing environmental aspects into product design and development or continuous improvement methodology for sustainable product development. Environmental performance as key performance indicators need to be addressed in continuous improvement processes and the product design and development process to achieve competitiveness of products (Pusporini, Abhary and Luong 2012). Pusporini, Abhary and Luong (2013d) demonstrated a concept of QFD approach to determine environmental requirements. There are two main advantages of the application of a QFD approach concerning environmental aspects that firstly integrate customer and environmental requirements into product design and development processes and secondly assist the expert team in a company in prioritising these requirements to provide a product with good quality and environmental friendliness.

4.2.1 Establish environmental requirements (whats)

The first important step in this stage is to identify environmental requirements referred to as *whats* (as called in QFD), i.e. what extent the products or processes meet environmental requirements (*ER*). To create an eco-friendly product, environmental requirements need to be embedded into QFD approach whose quantification can be structured via a variety of methods based on literature review, analysis of customer complaints, surveys, an operational report, historical data, discussion, and brainstorming with some experts in a manufacturing company. The use of these approaches will lead to a clear understanding of how critical the consideration of environment requirements are in the product design and development processes.

Several environmental requirements have been developed by Masui *et al.* (2003) who highlighted that when the expert team in a company wants to improve their product environmentally, the company has to capture the green voice of the customer. In addition, the identification of green voice of customer (green VOC) will involve consumers as users, recyclers, the government, and the environment. Also the authors developed and demonstrated how these requirements have influenced producing environmentally friendly products. For applications in industry these requirements may need to be added to other requirements appropriate to the industry circumstances. Examples of environmental requirements are illustrated in Table 4.1.

Table 4.1 Example of environmental requirements

Environmental Requirements
Less material consumption
Easy to transport and storage
Easy to process and assembly
Less energy consumption
High durability
Easy to reprocess and reuse
Easy to disassemble
Use recyclable materials
Reduce hazardous materials
Easy to clean
Easy to smash
Easy to sort
Safe to incinerate process
Safe to landfill
Harmless to the living environment
Low electromagnetic waves
Safe emission during production process
Possible to dispose environmentally friendly

The list of environmental requirements as seen in Table 4.1 can be used as a guide to determine environmental requirements into a real case in the industry. This list includes everything from the literature and those added for other requirements by the author's investigation. However, to make sure whether these requirements are comprehensive and sufficient enough in the real application of industry, several approaches like literature review, stakeholder demands, market pressure, customer complaints, government policy, rules and regulations can be used further to determine environmental requirements. Brainstorming and a deep discussion with the expert team in a company will also help to identify appropriate requirements

The identification of relationship between environmental requirements and environmental indicators in the design of environmentally friendly products is important. These requirements also may have a correlation with other qualitative indicators such as cost, quality and time.

Environmental requirements and indicators have great influence on achieving the environmental goals. For example less reprocessed material (environmental requirement)

affects the amount of reprocessed materials (environmental indicator) during the production process. If the environmental goal for this indicator is, say, less than 4% but the current performance, according to reports, is more than 4% then this performance indicates that there is a gap which has to be addressed as a potential improvement for the production. The performance gaps can be identified by the expert team during the measurement process and can be set as a basis for continuous improvement.

For real applications in a manufacturing company there are varieties of environmental requirements that can be adopted. These depend on the characteristic of the operation process, the environmental impact and also the policy of the organisational management of the company. Manufacturing industries have to specify environmental requirements appropriate to their processes, products and circumstances and prioritise them.

4.2.2 Establish environmental indicators (hows)

The second step of QFD approach is identification of *technical attributes* or *engineering characteristics (hows*, as called in QFD*),* i.e. the identification of environmental indicators (*hows*) which are related to environmental requirements used for EPE. Environmental requirements determined in the previous step will be translated into design criteria. Each environmental requirement (*whats*) are correlated with environmental indicators (*hows)*. For example, less energy consumption is correlated with the amount of reprocessed material and amount of energy consumption; and less material used is correlated with the amount of solid waste and amount of materials.

Indicators, as a basic and important part of environmental performance evaluation (EPE) process, will facilitate the collection of meaningful data and allow accurate expression of environmental information. Identification of indicators should be based on significant environmental aspects associated with the organisation's business activities. EPE should result in meaningful information about the environmental performance of the organisation.

Approaches like literature review, stakeholder demands, market pressure, customer complaints, government policy, rules and regulations can be used as a guide to determine environmental indicators. The identification of these indicators may become complex therefore it is necessary to use a systematic approach to identify them. A general

framework of a lifecycle product can be used to help the expert team in a manufacturing industry to identify appropriate indicators; discussions and brainstorming with some experts will also help.

Different industries use different indicators (*EMIs, ECIS or EPIS*) which depend on the organisation's management, policy and environmental goals. There are many categories of indicators (Henri and Journeault 2008; Jasch 2000; Masui *et al*. 2003; Olsthoorn *et al*. 2001; Rao *et al*. 2006; Thoresen 1999; Tsoulfas and Pappis 2008). Examples of environmental indicators are illustrated in Table 4.2.

There are characteristics of indicators to be considered including the right type, number of them (not too many not too few), simple and understandable, address important issues for customer satisfaction, can promote benchmarking, controllable, valid and verifiable. Too few or too many or wrong indicators can result in poor or misleading information. The indicators should provide adequate information to management in terms of meeting targets of EPE.

Table 4.2 Examples of environmental indicators

Engineering Characteristics
Quantity of materials
Quantity of recycled or reprocessed materials
Quantity of water used
Quantity of hazardous materials
Quantity of energy used per unit of product
Quantity of solid waste
Quantity of hazardous waste
Quantity of water waste
Energy efficiency
Air emission
Total waste for disposal
Quantity of waste stored on site

4.2.3 Presentation of fuzzy QFD with environmental concern

After identifying *whats* and *hows*, the next step is to construct house of quality (HOQ) including the relationship between *whats* and *hows*. The expert team needs to determine the weight of each environmental requirement and the relationship between *whats* and *hows*. The data analysis for the QFD method is commonly based on human assessment

that uses a particular rating scale. Rating scales 1 to 9 are used to identify the weight of each customer requirement (*whats*). Rating scale 1 indicates that this customer requirement is very unimportant and rating scale 9 indicates that the customer requirement is very important. Similar rating scale is also used to identify the relationship between environmental requirements (*whats*) and environmental indicators (*hows*), for example rating scales 1, 3, 5 and 9 where 1 indicates that the environmental requirement and environmental indicator are weakly related, while 3 is the indicative of a medium relationship and 9 of strong relationship.

It is well recognised that the use of qualitative information including human assessment is always subjective and vague and this is the main reason to integrate the fuzzy concept into the QFD method to account for this subjectivity and vagueness. Fuzzy QFD with environmental concerns to prioritise environmental indicators is illustrated in Figure 4.2.

The fuzzy logic in this stage is to support the contruction of the HOQ where experts from a company will be involved; an expert refers to a person who has extensive knowledge, skill and ability in some particular field based on their research, experience and occupation. The sample of fuzzy QFD to prioritise environmental indicators related to the designing of environmental performance evaluation will be presented in Chapter 5 (Modelling of environmental performance evaluation).

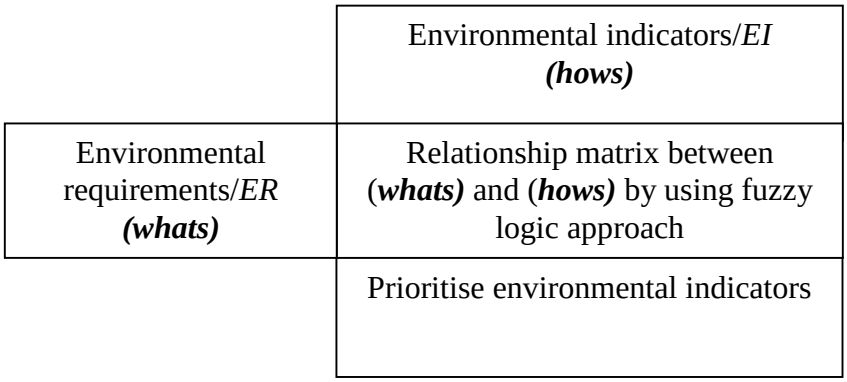


Figure 4.2 Fuzzy QFD with environmental concern

4.3 Design

Design, according the Figure 4.1, this stage is to determine the input and output variables of environmental performance evaluation model. To identify environmental indicators,

the expert team in a company can focus on the environmental indicators which achieve highest score at the previous stage (fuzzy QFD).

The basic concept for environmental performance evaluation is an operational system which corresponds to input-output of environmental indicators analysis. These involve formulating the design concept of environmental performance evaluation and identify its input and output variables and the relationship between these variables. Before develop this evaluation, the expert team in a company needs to clearly understand how to design process mapping for this evaluation. This implies that the team understands the major inputs 'x' and outputs 'y' of the environmental performance evaluation process as well as its interrelationship with other quality performance such as cost and time. As an illustrative example, the outline of environmental performance evaluation (EPE) based on ISO 14.031 which is similar with "*Plan-Do-Check-Act*" as a management system model (Jasch 2000) is depicted in Figure 4.3.

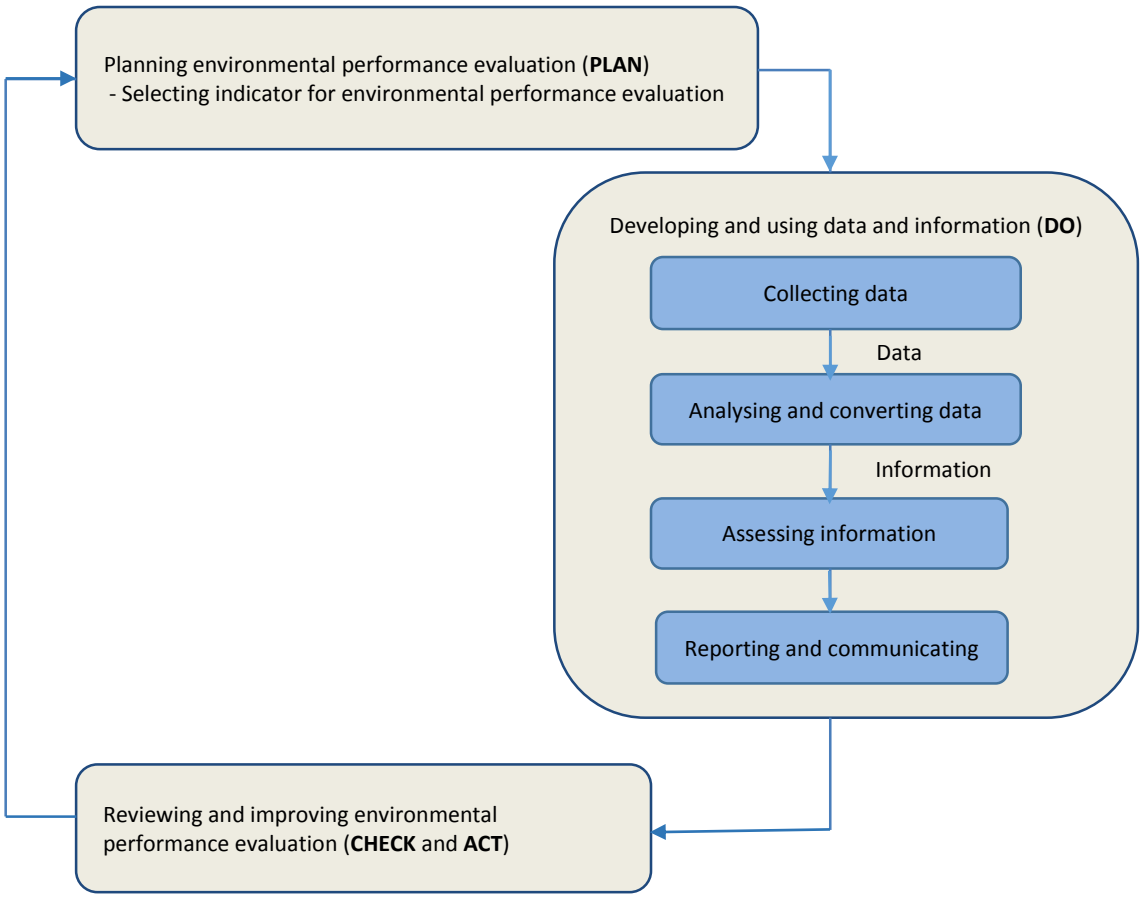


Figure 4.3 The environmental performance evaluation (EPE) process (adapted from Jasch 2000)

EPE can assist a manufacturing industry to determine whether it meets its goals, targets, and objectives. Environmental indicators during the EPE process will be measured and compared to the goals, targets and objectives in order to see if they have been achieved. A crucial part of the EPE process is the selection of appropriate and meaningful indicators showing how the organisation will impact on the environment. Indicators set in the heart of the entire EPE process.

To develop a model of environmental performance evaluation a set of selected environmental indicators are set as input variables to the model then the output variable is environmental performance. Environmental performance as a function of environmental indicators is introduced as a transfer algorithm as depicted in Figure 4.4. This algorithm consists a dependent variable (output variable/Y) and independent variables (input variables/Xs). This algorithm can help the expert team clearly understand a process of environmental performance evaluation, its variables and its relationship.

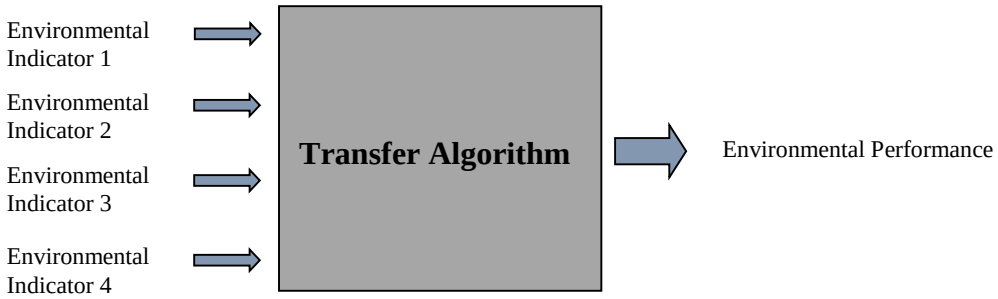


Figure 4.4 Transfer algorithm of input and output variables

4.4 Optimise

The process of environmental performance evaluation will be optimised by applying FIS and Taguchi method. The environmental performance evaluation is evaluated through the fuzzification of the environmental performance transfer algorithm.

The steps for measuring the environmental performance using FIS are: defining input and output variables in fuzzy format, identifying membership functions, identifying if-then rules, fuzzy solution results, and Taguchi method. The explanations of these steps are explained below.

4.4.1 Define input and output variables in fuzzy format

By applying fuzzy logic tool box from MATLAB, the transfer algorithm of input and output variables of the environmental performance evaluation in fuzzy format can be developed.

4.4.2 Develop membership function

A membership function is a linguistic term which maps each possible value of the linguistic variables to a real number between 0 and 1. Each linguistic term is equivalent to a range of possible values. In this step, after brainstorming and discussion, experts from different sections of the company decide on the fuzzy membership function corresponding to each input variable (environmental indicator) which are to be used in fuzzy analysis.

4.4.3 Develop if-then rules

In this step the relationships between input and output variables are established via fuzzy *if-then* rules. A fuzzy *if-then* rule consists of an *if* part (*antecedent*) and a *then* part (*consequent*). The antecedent is a combination of terms whereas the consequent is just one term. *If-then* rules follow the format *if (condition x) and (condition y) then (result z)*. Similar to the identification of membership functions for each input variable, the identification of if-then rules for the application of FIS also involves some experts' involvement.

4.4.4 Fuzzy solution result

The upper and lower specification limits of each input variable are used to in MATLAB fuzzy logic tool box to generate a set of fuzzy solutions. The output response, also produced graphically, is calculated as a score and then translated into linguistic terms.

4.4.5 Statistical approach / Taguchi method

Pusporini, Abhary and Luong (2013b) proposed the integration of a fuzzy inference system and Taguchi's experiment to design an environmental performance evaluation model. The Taguchi method is used to analyse the fuzzy results to determine the most significant environmental indicators to be considered by the company for improving their environmental impacts.

4.5 Validate

The validation of the proposed model is needed to ensure that it meets the environmental requirements in order to produce environmentally friendly products. This is illustrated in a Case Study in Chapter 6.

4.6 Concluding remarks

This chapter presented the modelling approach to environmental performance evaluation based on improved IDOV phases from DFSS, Fuzzy Logic, QFD and FIS. Then Taguchi method is conducted to analyse the model and determine the indicators with highest impact on the environment. Modelling of environmental performance evaluation will be presented in Chapter 5.

Chapter Five

Modelling of Environmental Performance Evaluation



5.1 Introduction

This chapter demonstrates the modelling of environmental performance evaluation via the approach explained in Chapter 4 where it was described that the development of environmental performance evaluation involves people's subjective and vague assessments, quantified by the application of fuzzy logic. Pusporini, Abhary and Luong (2013c) demonstrated using membership function from fuzzy expert system to design environmental performance evaluation. The authors proposed fuzzy rule with multi input variables and single output variables to develop the model. The authors also pointed out that using fuzzy expert system in this evaluation will provide greater flexibility when acquiring expert knowledge from manufacturing companies and also this scheme can be incorporated with other qualitative information such as experience and expert judgments.

In addition Pusporini, Abhary and Luong (2013) proposed a comprehensive framework for evaluating environmental performance using the hybrid of FIS and Taguchi method where they demonstrated the application of this integration in the design of environmental performance evaluation which consists of linguistic terms and subjective information.

In this chapter, the approach explained in Chapter 4 is followed step by step to build up the model. According to Figure 4.1 the flow of DFSS for environmental performance evaluation model consists of four steps of IDOV activities (*identify, design, optimise* and *validate*). These activities, specifically tailored for the environmental evaluation model, will be explained in details below.

5.2 Identify

Identify, the first step of IDOV, refers to the quantitative presentation of fuzzy QFD with environmental concern.

5.2.1 Determine environmental requirements and environmental indicators

To conduct QFD method it is important to determine environmental requirements and environmental indicators. From Section 4.2.1 and 4.2.2 environmental requirements and indicators have been listed. Then discussion and brainstorming with the expert team in a company need to be conducted to determine what environmental requirements and indicators are which appropriate with company's circumstances.

5.2.2 Translate environmental requirements and environmental indicators into HOQ

Once environmental requirements and indicators established, the next step is translating them into HOQ. This step involves expert judgments. Using fuzzy logic, expert judgements will be transformed into triangular fuzzy numbers (TFNs). TFNs are chosen due to their computational simplicity and usefulness in processing the fuzzy information. Li (1999) proposed a fuzzy model with solution algorithm to group decision making. A stepwise algorithm of fuzzy QFD approach is developed herein:

Step 1: identify the linguistic terms as triangular fuzzy number to represent the weight of environmental requirements and their relationship with environmental indicators.

Easy-to-understand and apply linguistic terms from Kuo, Wu and Shieh (2009) are used to represent expert assessment in HOQ. These are five linguistic terms to represent the weight of environmental requirements, namely *very unimportant (VU), unimportant (U), medium (M), important (I), and very important (VI)*. These linguistic terms are transformed into triangular fuzzy number (TFNs) as seen in Table 5.1.

Similarly linguistic terms are employed to identify the relation matrix between environmental requirements (*whats*) and environmental indicators (*hows*) as shown in Table 5.2.

Table 5.1 Linguistic terms for environmental requirements

Linguistic Term	Crisp value	Triangular Fuzzy Number
Very unimportant	1	(1,1,2)
Unimportant	3	(2,3,4)
Medium	5	(4,5,6)
Important	7	(6,7,8)
Very important	9	(8,9,9)

Step 2: Determine and calculate aggregate fuzzy importance weight of environmental requirements based on expert knowledge

During the construction of HOQ in QFD, experts will be involved to quantify their assessments by scoring the linguistic terms in Table 5.1 from which the *aggregate fuzzy importance weight* of environmental requirements are calculated by

$$\hat{w}_j = \frac{1}{k}\left(\sum_{i=1}^{k} a_{ij}, \sum_{i=1}^{k} b_{ij}, \sum_{i=1}^{k} c_{ij}\right) = \frac{1}{k}\left(a_j, b_j, c_j\right) \tag{5.1}$$

Table 5.2 Linguistic terms for relationship matrix between *whats* and *hows*

Linguistic Term	**Crisp value**	**Triangular Fuzzy Number**
Very weak	1	(1,1,2)
Weak	3	(2,3,4)
Medium	5	(4,5,6)
Strong	7	(6,7,8)
Very strong	9	(8,9,9)

Where i = expert number, j = number of the environmental requirements = 1, 2, …, m, k = no. of experts, (a_{ij}, b_{ij}, c_{ij}) = the TFN chosen from Table 5.1 by expert number i for environmental requirement j, and (a_j, b_j, c_j) = the average TFN for environmental requirements j.

The aggregate fuzzy importance weight is changed into crisp value via defuzzification (Bottani 2009; Yager 1981) as follow:

$$w_j = \frac{a_j + 2b_j + c_j}{4} \tag{5.2}$$

which is a component of the vector of environmental requirements

$$\{w\} = \{w_1, w_2, ..., w_m\}^T \tag{5.3}$$

Step 3: Determine and calculate the relationship between environmental requirements and environmental indicators

Similar to *Step 2*, experts will be involved to quantify their assessment by scoring via the linguistic terms in Table 5.2 from which the *aggregate fuzzy relationship* between environmental requirements (*ER*) and environmental indicators (*EI*) are calculated by

$$r_{ij} = \frac{1}{k}\left(\sum_{i=1}^{k} x_{ij}^{l}, \sum_{i=1}^{k} y_{ij}^{l}, \sum_{i=1}^{k} z_{ij}^{l}\right) = \frac{1}{k}(x_j, y_j, z_j) \tag{5.4}$$

Where l = expert number, k = no. of experts, i = *sequence no. of* ER_i , j = *sequence no. of* EI_j $(x_{ij}^{l}, y_{ij}^{l}, z_{ij}^{l})$ = the TFN chosen from Table 5.2 by expert number l for ER_i and EI_j and (x_j, y_j, z_j) = the average TFN for ER_i EI_j.

Using Equation 5.4 the relationship between environmental requirements (*ERs*, *whats*) and environmental indicators (*EIs, hows*), namely [r], is obtained and illustrated according to Equation 5.4 where r_{ij} is the relationship fuzzy number between ER_i and EI_j.

$$[r] = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{5.5}$$

Step 4: Calculate the value of environmental indicators

The value of environmental indicators is the product of weight of environmental requirements $\{w\}$ and relationship $[r]$ and calculated by

$$\{A\}^T = \{w\}^T [r] \tag{5.6}$$

Because r_{ij} consists of three TFN of relationship between ER_i and EI_j, each element of $\{\hat{A}\}$, i.e. A_j would also consists of three TFN elements A_{j1}, A_{j2} and A_{j3}. Therefore element j of vector {A} is

$$A_j = \frac{A_{j1} + 2A_{j2} + A_{j3}}{4} \tag{5.7}$$

which is the defuzzification of environmental indicators j.

The fuzzy QFD result demonstrates the importance of each environmental indicator for the environmental performance evaluation. The expert team will focus on environmental indicators that achieve the highest score for the improvement target. For an illustrative example: consider three experts assessing waste reduction (environmental requirement) by identifying their weights (6, 7, 8), (6, 7, 8), (8, 9, 9) respectively as depicted in Table 5.3 Column a, b and c.

The example of aggregate fuzzy importance weight of environmental requirements based on expert's knowledge is depicted in Table 5.3, where figures in column (d) are calculated from Equation 5.1, the aggregate fuzzy importance weight of waste reduction; say for ER_1.

$\hat{w}_1 = (6 + 6 + 8; 7 + 7 + 9; 8 + 8 + 9)/3$

= (6.67; 7.67; 8.33) green-shaded figures in Table 5.3 Column d.

and figures in column (e) are calculated from Equation 5.2, the crisp value of aggregate importance of waste reduction, say for ER_1.

$w_1 =$ [6.67 + (2 x 7.67) + 8.33]/4 = 7.58 green-shaded figure in Table 5.3 Column e.

Similarly, three experts assess materials (environmental indicator) to identify the relationship between materials and waste reduction (*ER*) and the scoring given are (6, 7, 8), (6, 7, 8), (4, 5, 6) respectively as depicted in Table 5.4 Column a, b, and c.

The example of relationship between environmental requirements and environmental indicators based on experts' knowledge is depicted in Table 5.4, where figures in column (d) are calculated from Equation 5.4, the relationship between materials and waste reduction, say for ER_1 .

r_{11} = (6 + 6 + 4; 7 + 7 + 5; 8 + 8 + 6)/3

= (5.33; 6.33; 7.33) green-shaded figures in Table 5.4.

Then, the value of environmental indicators can be calculated from Equation 5.6 where, say the value of materials (*EI*) for waste reduction (*ER*)

$$A_j = \sum_{i=1}^{m} w_j r_{ij} \tag{5.8}$$

Therefore in the hypothetical example, the value of say A_1

$$A_1 = w_1 r_{11} + w_2 r_{21} + ... + w_m r_{m1} \tag{5.9}$$

Where w_i are calculated in Table 5.5 Column a and r_{ij} are tabulated in Table 5.5 Column b. The terms on the right side of Equation 5.10 are calculated and tabulated in Table 5.5 where as an example:

$w_1 r_{11}$ = 7.58 x (5.33; 6.33; 7.33).

= (40.44; 48.03; 55.61) green-shaded figures in Table 5.5 Column c.

Corresponds to ER_1 and EI_1 and its defuzzification is

= [40.44 + (2 x 48.03) + 55.61] /4 = 48.03 green-shaded figures in Table 5.5 Column d.

Table 5.6 shows the full results for the hypothetical example and ranking of *EI*. The result of house of quality (HOQ) in Table 5.5 demonstrates that the energy consumption has highest level of importance (357.66) followed by solid waste (282.93), reprocessed materials (257.08), emission (218.28), water pollutant (208.92), materials (204.65), water consumption (200.31), toxicity materials (145.31) and noise/vibration (118.53) respectively. The expert team would focus on the highest scores such as energy consumption, solid waste, and reprocessed materials.

Table 5.3 The example of aggregate fuzzy importance weight of environmental requirements from hypothetical experts' knowledge

Environmental requirements		Expert 1 **(a)**			Expert 2 **(b)**			Expert 3 **(c)**			Fuzzy average (Equation 5.1) **(d)**			Defuzzification (Equation5.2)
		a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	**(e)**
ER_1	Waste reduction	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33	7.58
ER_2	Pollution impact reduction	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00	7.00
ER_3	Less material usage	4	5	6	8	9	9	6	7	8	6.00	7.00	7.67	6.92
ER_4	Less energy usage	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67	8.17
ER_5	Less water usage	4	5	6	4	5	6	4	5	6	4.00	5.00	6.00	5.00
ER_6	Easy to process	4	5	6	6	7	8	4	5	6	4.67	5.67	6.67	5.67
ER_7	Safer to landfill	4	5	6	6	7	8	6	7	8	5.33	6.33	7.33	6.33
ER_8	Safer emission	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33	6.33
ER_9	Less harmful to the living environment	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33	6.33
ER_{10}	Disposable	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33	6.33

Table 5.4 The example of relationship matrix between environmental requirements and environmental indicators from hypothetical experts' knowledge

Environmental requirements		EI_1 : Materials											
		Expert 1 **(a)**			Expert 2 **(b)**			Expert 3 **(c)**			Average **(d)**		
		x	*y*	*Z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_2	Pollution impact reduction	0	0	0	0	0	0	0	0	0	-	-	-
ER_3	Less material usage	8	9	9	6	7	8	8	9	9	7.33	8.33	8.67
ER_4	Less energy usage	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	6	7	8	8	9	9	6	7	8	6.67	7.67	8.33
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	0	0	0	0	0	0	0	0	0	-	-	-
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Table 5.5 The example of the calculation of the value of environmental indicators

Environmental requirements		The value of environmental indicators (EI_1: Materials)							
		w **(a)**	*r* **(b)**			Elements of A_1 **(c)**			Defuzzification (Equation 5.7) **(d)**
			x	*y*	*z*	A_{11}	A_{12}	A_{13}	
ER_1	Waste reduction	7.58	5.33	6.33	7.33	40.44	48.03	55.61	48.03
ER_2	Pollution impact reduction	7.00	-	-	-	-	-	-	-
ER_3	Less material usage	6.92	7.33	8.33	8.67	50.72	57.64	59.94	56.49
ER_4	Less energy usage	8.17	6.00	7.00	8.00	49.00	57.17	65.33	57.17
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	6.67	7.67	8.33	37.78	43.44	47.22	42.97
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	-	-	-	-	-	-	-
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Table 5.6 The example of fuzzy QFD result to prioritise environmental indicators

	Environmental req.	**Weight**	***EI*$_1$ Materials**	***EI*$_2$ Tox. Mat**	***EI*$_3$ Rep.mat**	***EI*$_4$ Energy cons.**	***EI*$_5$ Water cons.**	***EI*$_6$ Emission**	***EI*$_7$ Noise/vib.**	***EI*$_8$ Water pollutan**	**EI$_9$ Solid waste**
ER$_1$	Waste reduction	7.58	48.03	-	61.93	57.51	48.03	42.97	42.97	48.03	61.93
ER$_2$	Pollution impact reduction	7	-	57.17	-	57.17	39.67	39.67	39.67	49	44.33
ER$_3$	Less material usage	6.92	56.49	-	52.45	43.81	-	-	-	-	48.42
ER$_4$	Less energy usage	8.17	57.17	-	66.69	71.46	-	51.72	-	-	-
ER$_5$	Less water usage	5	-	-	-	-	40.83	-	-	31.67	-
ER$_6$	Easy to process	5.67	42.97	-	35.89	35.89	-	-	-	-	-
ER$_7$	Safer to landfill	6.33	-	-	-	-	-	-	-	-	48.03
ER$_8$	Safer emission	6.33	-	-	-	51.72	-	48.03	-	-	-
ER$_9$	Less harmful to the living environment	6.33	-	48.03	40.11	40.11	35.89	35.89	35.89	40.11	40.11
ER$_{10}$	Disposable	6.33	-	40.11	-	-	35.89	-	-	40.11	40.11
	Total A_j		**204.65**	**145.31**	**257.08**	**357.66**	**200.31**	**218.28**	**118.53**	**208.92**	**282.93**
	Percentage of A_j		**10.27**	**7.29**	**12.89**	**17.94**	**10.05**	**10.95**	**5.95**	**10.48**	**14.19**
	Rank		**6**	**8**	**3**	**1**	**7**	**4**	**9**	**5**	**2**

5.3 Design

According to Pusporini, Abhary and Luong (2013a), in current practice of product design and development, the key performance indicators (KPI) commonly focus on a traditional approach which considers three areas of performance as depicted in Figure 5.1.

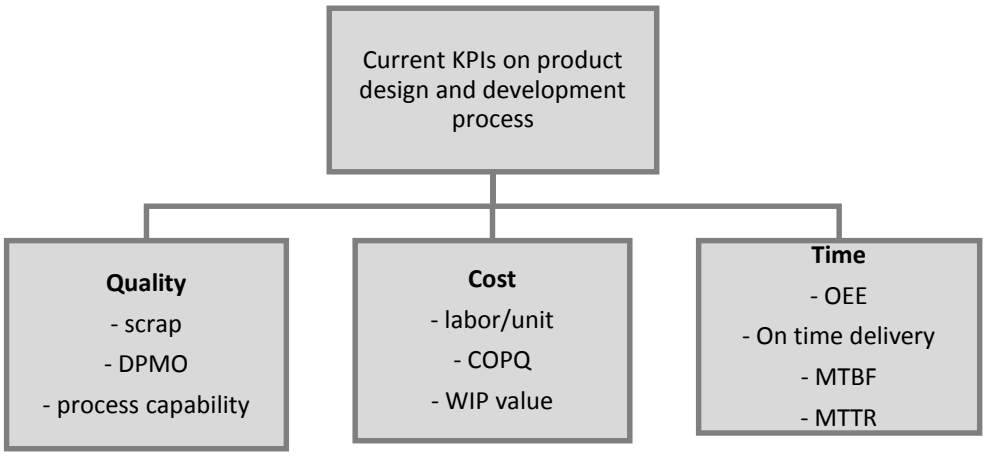


Figure 5.1 Current key performance indicators (KPIs) for product design and development process (Pusporini, Abhary and Luong 2013a)

It can be seen that there is no consideration of including the environmental performance in product design and development. Also the authors stated that consideration of both quality and environmental performance will lead to competitive products as depicted in Figure 5.2.

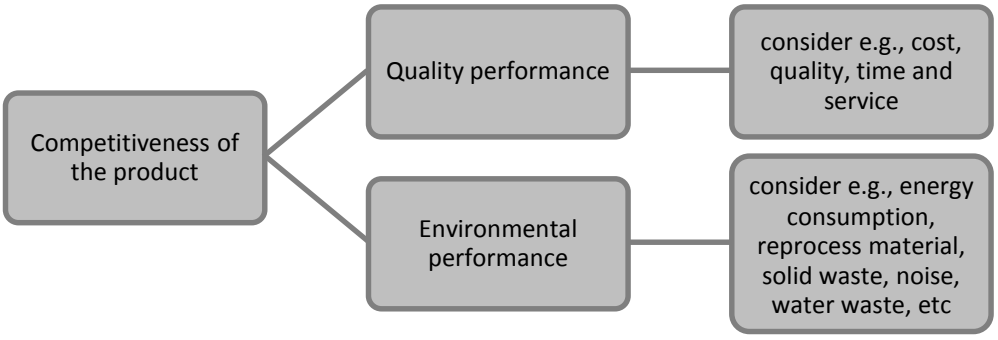


Figure 5.2 Key performance indicators for the competitiveness of the product

As described in Section 4.3 the environmental performance (*EP*) is a function of environmental performance indicators (*EI*) and shown in Equation 5.10.

$$EP = f(EI) \tag{5.10}$$

This relationship is established via transfer algorithm herein. For the hypothetical example in the previous stage, based on the fuzzy QFD results and Equation 5.10, the expert team focuses on three significant environmental indicators namely: *reprocessed materials* (*R*), *solid waste* (*S*) and *energy consumption* (*E*) and the environmental performance (*EP*) can be described as a function of three environmental indicators provided and given as in Equation 5.11.

$$EP = f(R, S, E) \tag{5.11}$$

Any slightly increase or decrease in the amount of energy consumption or reprocessed materials and solid waste can possibly impact on the environmental performance. The environmental performance (output) is the key metric for monitoring and controlling the environmental indicators.

5.4 Optimise

The process of environmental performance evaluation will be optimised by applying integration of FIS and Taguchi Method. The five main steps in this stage, explained in Chapter 4 namely: define input and output variables in fuzzy format, develop membership function, develop *if-then* rules, fuzzy solution results from MATLAB fuzzy logic tool box, and Taguchi Method are implemented as follows.

5.4.1 Selection input and output variables

Input variables are in fact the selected environmental indicators from fuzzy QFD results. In the ongoing hypothetical example the three environmental indicators, namely *reprocessed materials (R), solid waste (S), and energy consumption (E)* which had significant correlation with environmental performance are the input variables to the proposed model, and the output variable of the proposed model is environmental performance. The FIS is applied and transfer algorithm is developed to represent the relationship between input and output variables. MATLAB fuzzy logic toolbox is employed to present input and output variables for the proposed model in fuzzy format as seen in Figure 5.3.

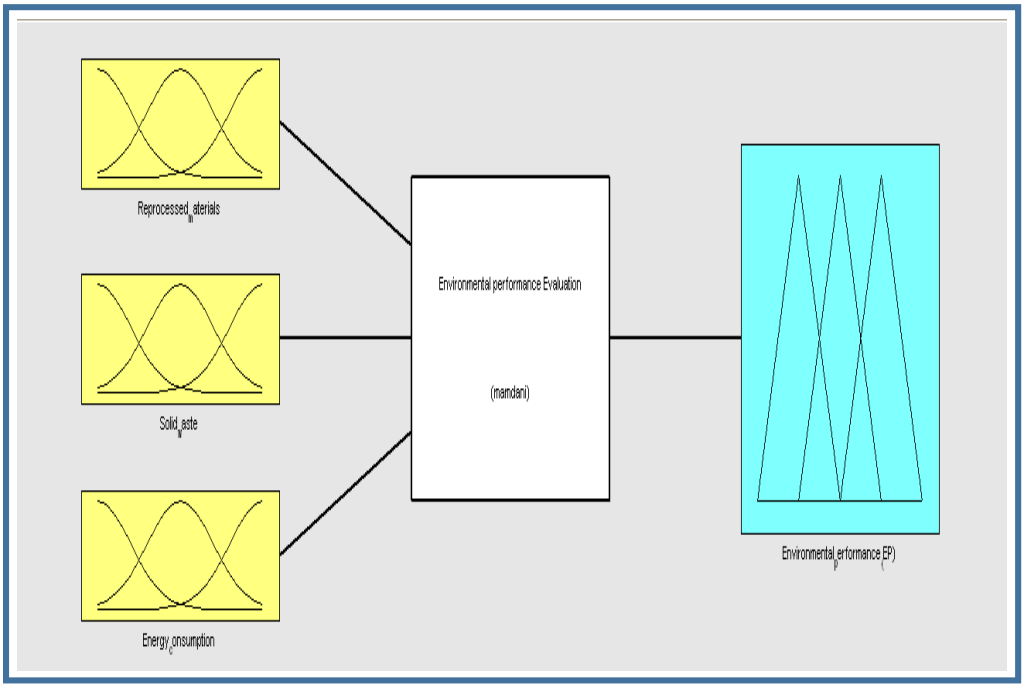


Figure 5.3 Input and output variables in fuzzy format

5.4.2 Develop membership function

For the ongoing example the membership functions are developed as follows.

Reprocessed materials (R)

Reprocessed materials are measured based on the percentage of materials reprocessed during the production process for which five categories are assumed here: very high (say more than 5%), high, medium, low and very low (say less than 1%). The range of reprocessed materials can be set as per Table 5.7 whose fuzzy membership function, from MATLAB is shown in Figure 5.4.

Table 5.7 Linguistic terms and measurement for reprocessed materials

Linguistic Terms	Range (% of Reprocessed Materials)
Very High	> 5
High	from 3 to 5
Medium	from 2 to 4
Low	from 1 to 3
Very Low	< 1

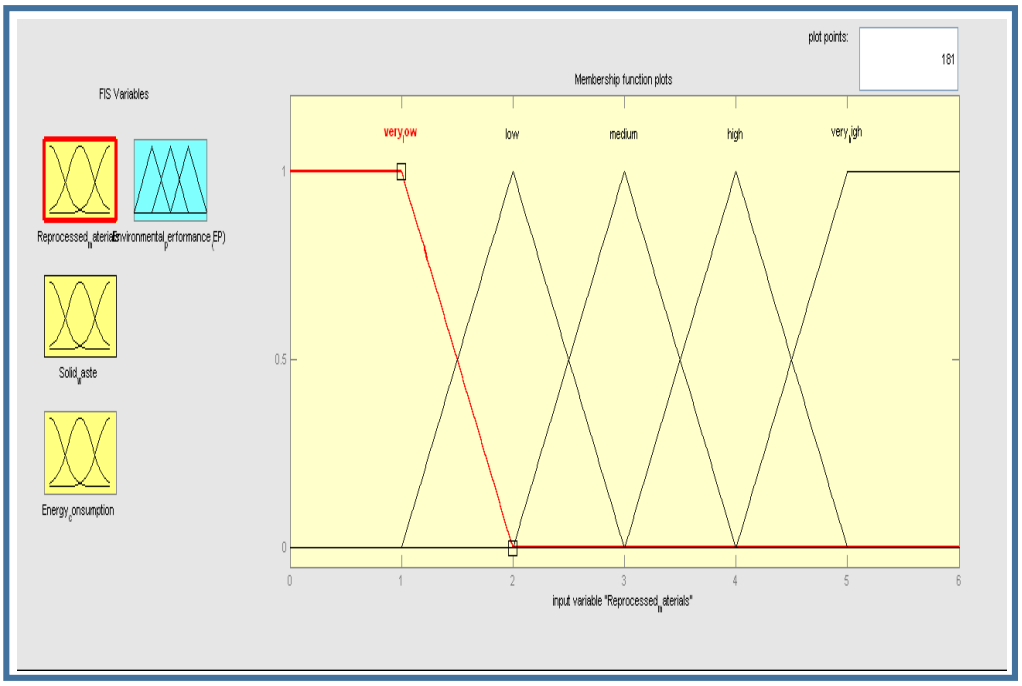


Figure 5.4 Fuzzy membership function for reprocessed materials from MATLAB

Solid waste (S)

Solid waste is measured based on the amount of solid waste produced during the production process for which five categories are assumed here: very high (say more than 0.9%), high, medium, low, and very low (say less than 0.5%). The categories of solid waste can be seen in Table 5.8 and the corresponding membership function can be seen in Figure 5.5.

Table 5.8 Linguistic terms and measurement for solid waste

Linguistic Terms	**Range (% of Solid Waste)**
Very High	> 0.9
High	from 0.7 to 0.9
Medium	from 0.6 to 0.8
Low	from 0.5 to 0.7
Very Low	< 0.5

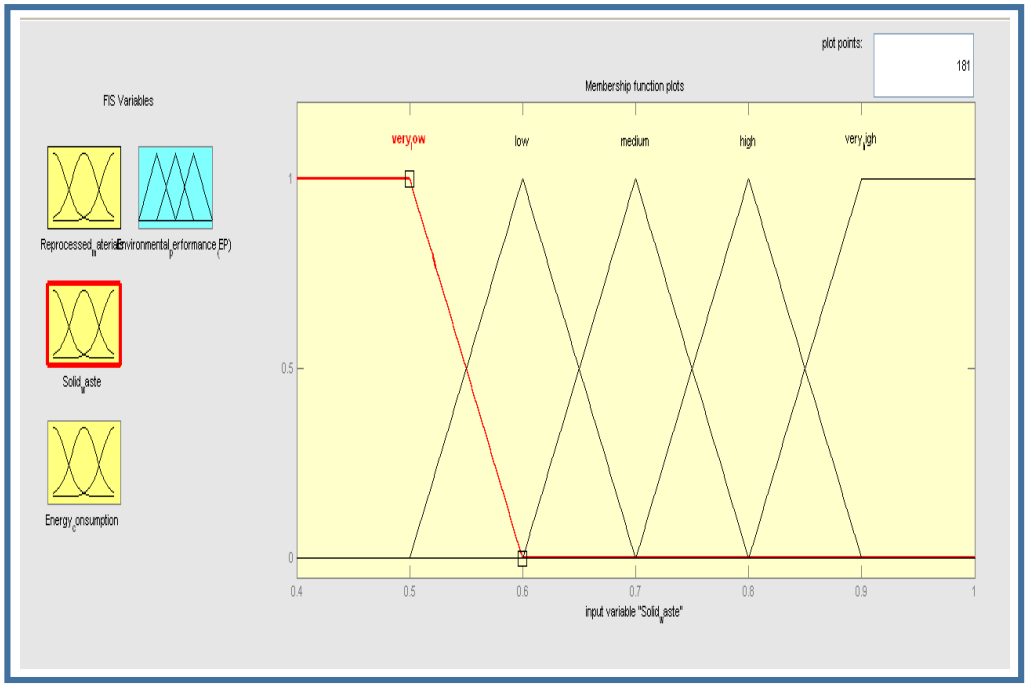


Figure 5.5 Fuzzy membership function for solid waste from MATLAB

Energy consumption (E)

Energy consumption is measured based on the amount of energy consumed by products for which three categories are assumed here: high (more than 0.15 kWh/unit), medium, and low (less than 0.05kWh/unit). The categories of energy consumption can be seen in Table 5.9 and the corresponding membership function is shown in Figure 5.6.

Table 5.9 Linguistic terms and measurement for energy consumption

Linguistic Terms	**Energy Consumption per unit product (Kwh/unit product)**
High	> 0.15
Medium	from 0.05 to 0.15
Low	< 0.05

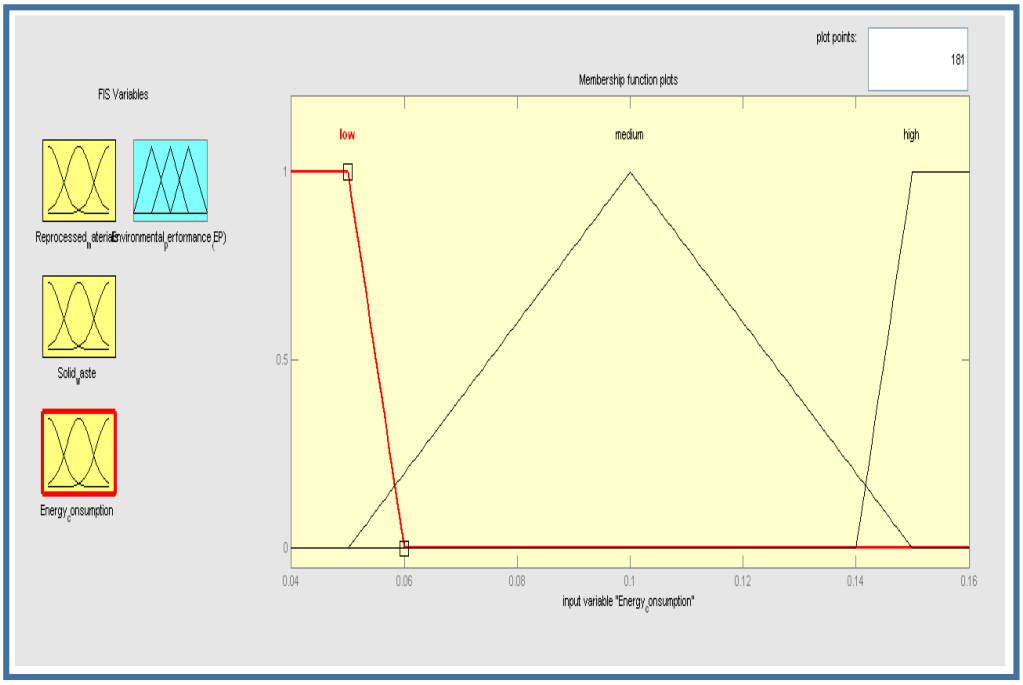


Figure 5.6 Fuzzy membership function for energy consumption from MATLAB

Output Variable

The output variable is environmental performance based on the indicators provided as input variables. It is presented in linguistic terms that can be transformed into numerical value, namely: very poor (between 0 and 0.30), poor (between 0.31 and 0.50), moderate (between 0.51 and 0.70), satisfied (between 0.71 and 0.90), and optimum (between 0.91 and 1), as depicted in Table 5.10. The optimum range indicates that the environmental performance has reached a level that fulfils the requirements and requires the environmental evaluation process and environmental indicators to be continuously monitored and maintained. The membership function of output variable can be seen in Table 5.10 and Figure 5.7.

Table 5.10 Range of environmental performance and linguistic value (output)

Linguistic Terms	**Value**
Optimum	0.91-1.0
Satisfied	0.71-0.90
Moderate	0.51-0.70
Poor	0.31-0.50
Very Poor	0.00- 0.30

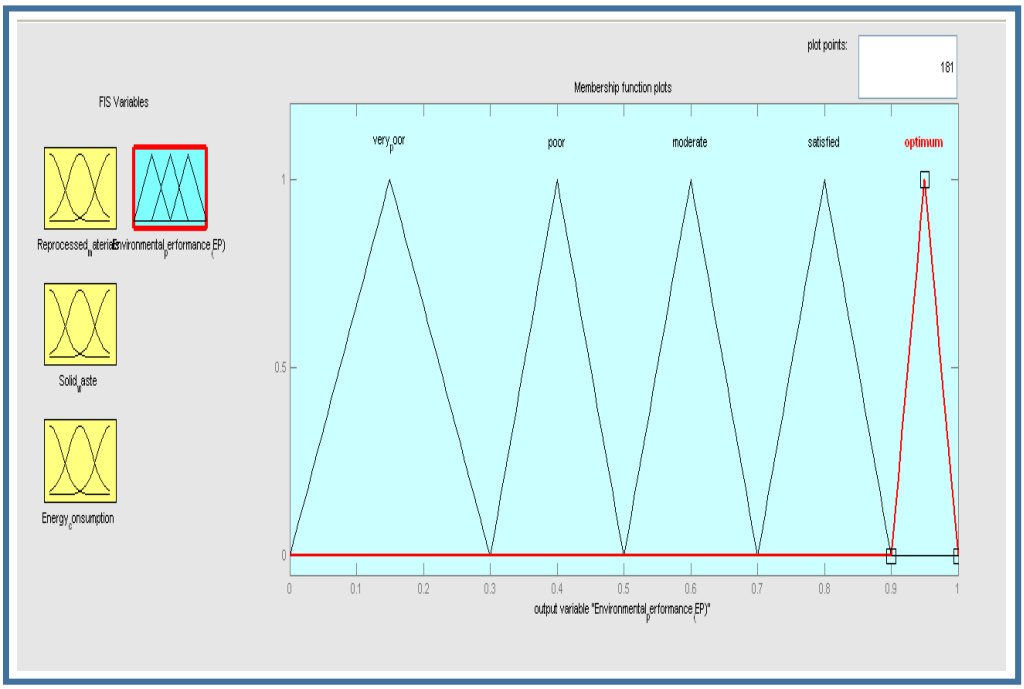


Figure 5.7 Membership function for output variable from MATLAB

5.4.3 Develop if-then rules

Similar to the identification of membership function for each input variable, by conducting brainstorming and discussion with experts in the manufacturing industry, fuzzy *if then* rules will be developed as *if (condition x) and (condition y) then (result z)*. For example: *if energy consumption is high and reprocessed materials is high and solid waste is high then environmental quality is very poor.*

Table 5.11 The sample of *if-then* rules

Energy consumption is low					
Reprocessed materials / **Solid Waste**	Very high	High	Medium	Low	Very low
Very high	Moderate	Moderate	Moderate	Satisfied	Satisfied
High	Moderate	Moderate	Moderate	Satisfied	Satisfied
Medium	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Low	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Very low	Moderate	Moderate	Satisfied	Satisfied	Optimum

Table 5.11 presents the sample of *if-then* rules for the above-mentioned example of the three environmental indicators *(energy consumption, reprocessed material* and *solid waste*). The corresponding rule viewer from fuzzy inference system (FIS) can be seen in Figure 5.8.

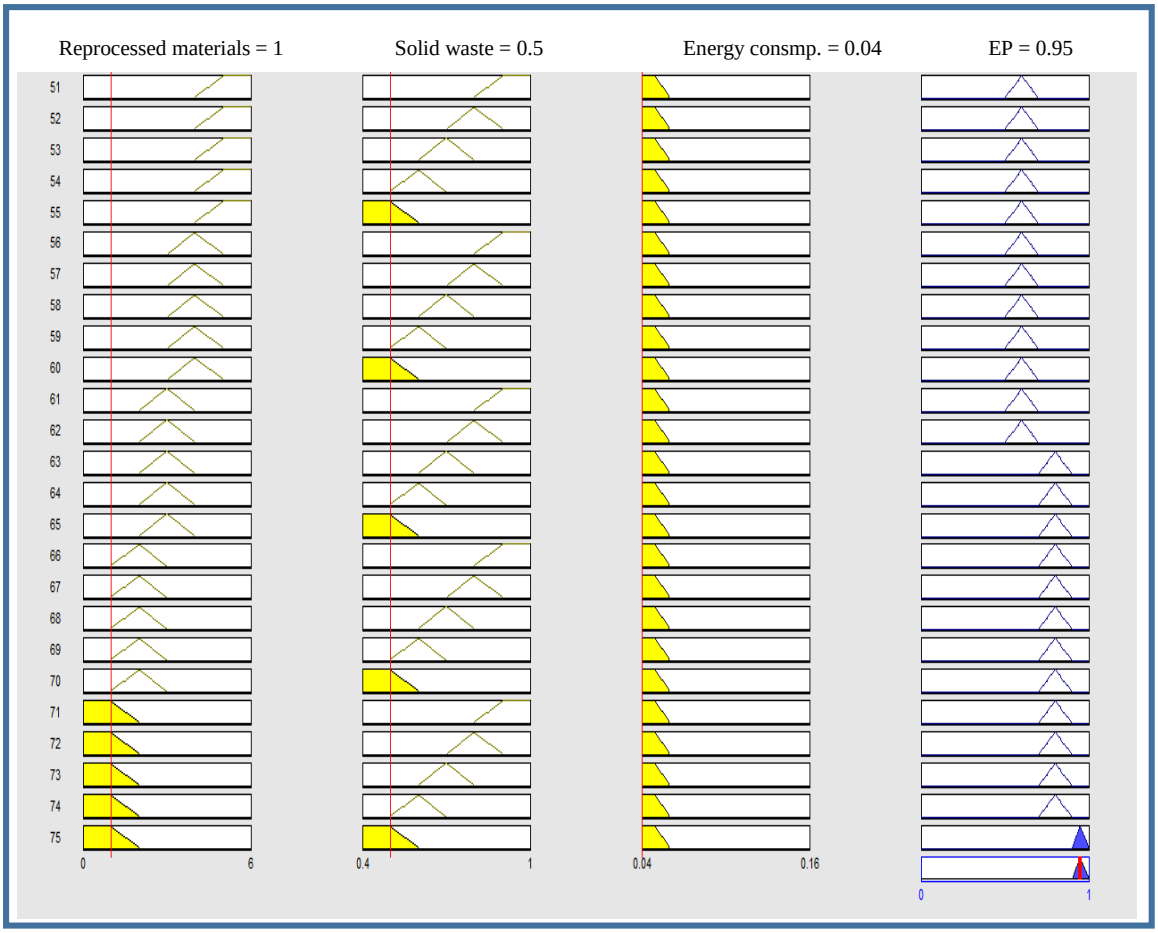


Figure 5.8 The sample of rule viewer from fuzzy MATLAB

The number of these *if-then* rules depends on the number of membership function of each input variable which would increase or decrease the number of rules significantly. For example, the assumed model has three input variables namely: reprocessed materials (with 5 membership function), solid waste (with 5 membership function), and energy consumption (with 3 membership function), then the number of *if-then* rules is $5 \times 5 \times 3 = 75$.

A sample of 75 fuzzy rules from FIS is depicted in Figure 5.8. This figure shows that the value of environmental indicators can be set to achieve certain environmental performance. The value of each indicator can be changed to be lower or higher and the

environmental performance can be calculated. For example, if the value of reprocessed materials, solid waste and energy consumption are 1, 0.5, 0.04 respectively, then the environmental performance is 0.95 as depicted in Figure 5.8 (rule number 75).

The rules viewer as shown in Figures 5.8 also demonstrates the extent to which the environmental indicators will impact the environmental performance. The specification limits of each input variable can be set higher or lower by dragging the red line (on the monitor) to the right (high) or to the left (low) and then the environmental performance (output) can be automatically calculated.

5.4.4 Fuzzy-solution results from MATLAB fuzzy logic tool box

A set of fuzzy solutions is generated using MATLAB fuzzy logic tool box. The upper and lower specification limits of each input variable are set and then the output response is calculated as a score, then translated into linguistic terms. A graphical surface presents the influence of two input variables on the environmental performance (output variable), and they are three namely: the influence of reprocessed materials and solid waste, the influence of reprocessed materials and energy consumption, and the influence of solid waste and energy consumption as depicted in Figure 5.9, 5.10 and 5.11 respectively.

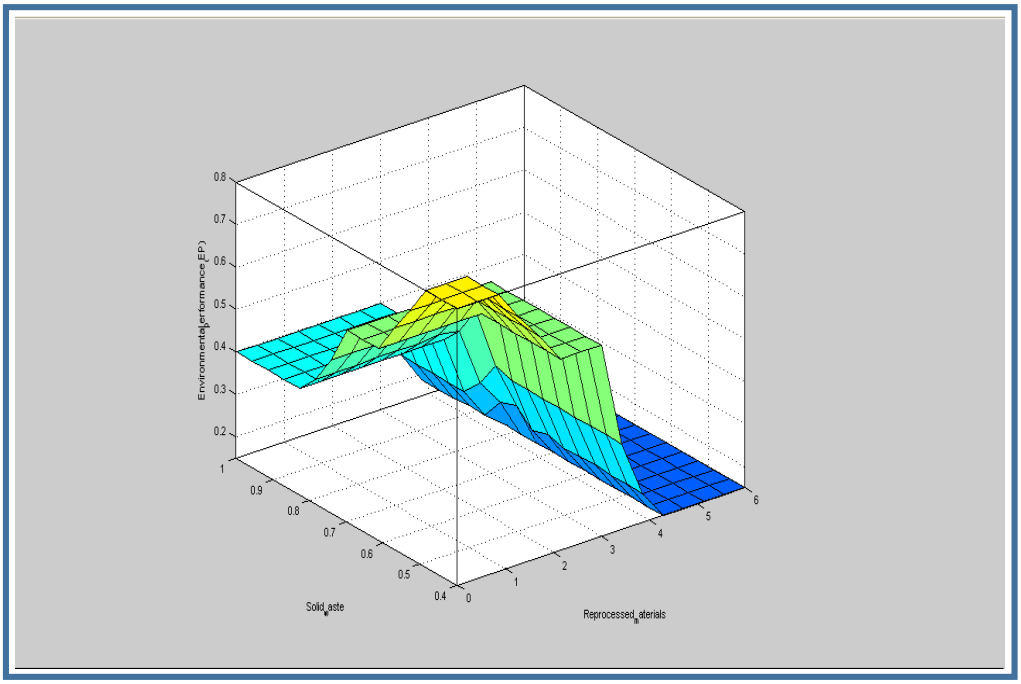


Figure 5.9 Graphical surfaces for influence of reprocessed materials and solid waste on environmental performance

Figure 5.9 shows that the influences of reprocessed materials and solid waste on environmental performance are close, while energy consumption is more influential than reprocessed materials, Figure 5.10, and solid waste, Figure 5.11.

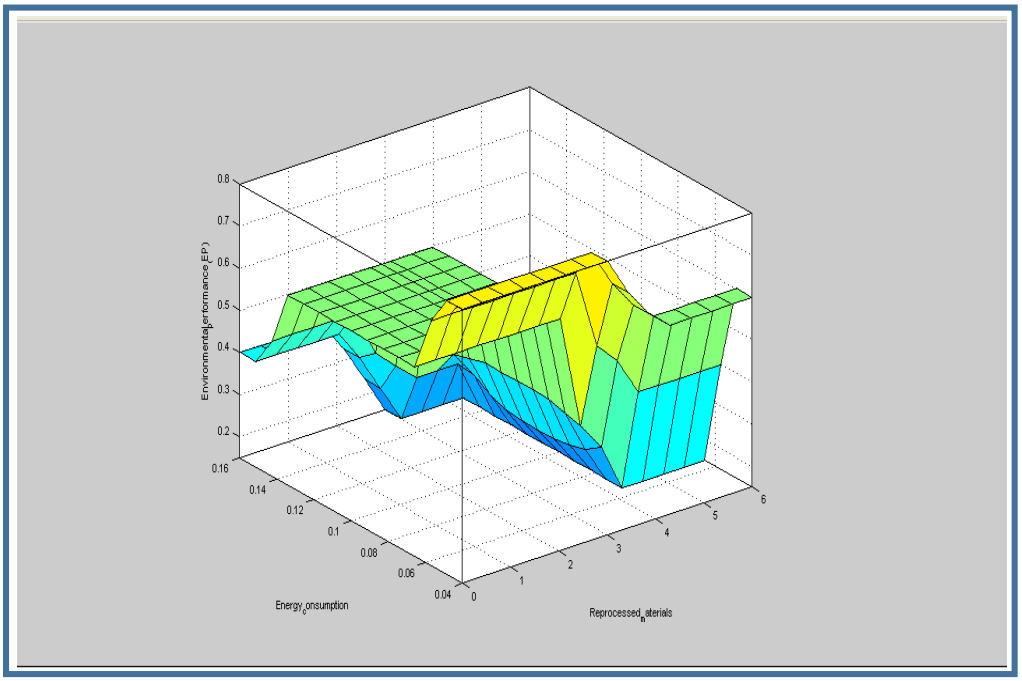


Figure 5.10 Graphical surfaces for influence of reprocessed material and energy consumption on environmental performance

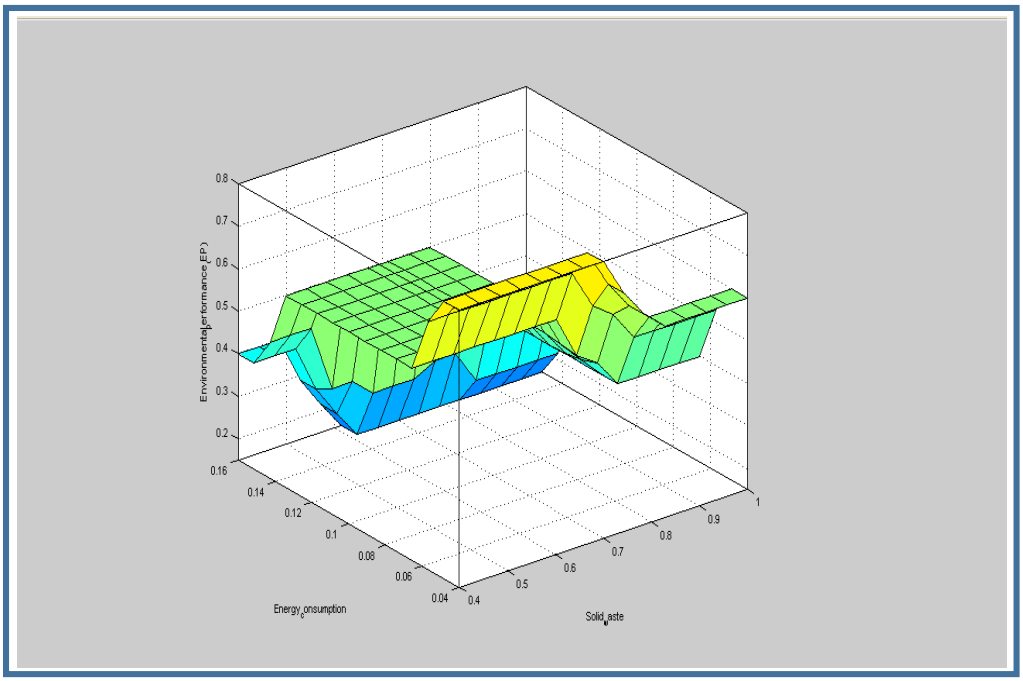


Figure 5.11 Graphical surfaces for influence of solid waste and energy consumption on environmental performance

Taguchi Method is now employed to analyse the fuzzy results to determine the degree of significance of the environmental performance indicators as explained below.

5.4.5 Taguchi method (statistical analysis)

MINITAB is used to analyse Taguchi method. Pusporini, Abhary and Luong (Pusporini, Abhary and Luong 2013b) proposed the integration of fuzzy inference system and Taguchi's experiment to analyse and elicit the main contribution of the environmental indicators in environmental performance. The outcome of Taguchi's experiment will be, in fact, prioritising the environmental indicators, as a recommendation to the company, to improve their environmental indicator. To conduct the experiment, there are three main steps to follow in Taguchi method namely: identification of parameter design, identification of level of factor, and selection of orthogonal array; they are explained below.

a. Identification of parameter design

The identification of parameter design for Taguchi's experiment involves input and output variables from the fuzzy result in the previous step, based on which there are three significant environmental indicators (*reprocessed materials*, *solid waste*, and *energy consumption*) for the hypothetical example. The environmental performance is classified optimum if the improvement on the environmental performance reaches the higest range., i. e. *larger the better* (LTB).

b. Identification of level of factor

To conduct Taguchi's experiments the three selected environmental indicators in the hypothetical example are set as controllable factors and the expert team determines the level of each factor (parameter), say high, medium, and low. The number of level of factor, Table 5.12, determines the type of orthogonal array for the experiment.

Table 5.12 Level of factor

Factors	level 1	level 2	level 3
Reprocessed material	Low (1)	Medium (3)	High (5)
Solid waste	Low (0.5)	Medium (0.7)	High (0.9)
Energy consumption	Low (0.04)	Medium (0.1)	High (0.16)

c. Selection of orthogonal array to conduct the experiment

The orthogonal array depends on the level of factor previously determined. For the ongoing hypothetical example the orthogonal array $L_9(3^4)$ should selected to conduct the experiment. Combination of all nine experiments are set as follows:

Experiment1: reprocessed materials is set at level 1 (1), solid waste is set at level 1 (0.5), energy consumption is set at level 1 (0.04), then the environmental performance is 0.95.

Experiment 2: reprocessed materials is set at level 1 (1), solid waste is set at level 2 (0.7), energy consumption is set at level 2 (0.1), then the environmental performance is 0.6.

Experiment 3: reprocessed materials is set at level 1 (1), solid waste is set at level 3 (0.9), energy consumption is set at level 3 (0.16), then the environmental performance is 0.15.

Experiment 4: reprocessed materials is set at level 2 (3), solid waste is set at level 1 (0.5), energy consumption is set at level 2 (0.1), then the environmental performance is 0.6.

Experiment 5: reprocessed materials is set at level 2 (3), solid waste is set at level 2 (0.7), energy consumption is set at level 3 (0.16), then the environmental performance is 0.15.

Experiment 6: reprocessed materials is set at level 2 (3), solid waste is set at level 3 (0.9), energy consumption is set at level 1 (0.04), then the environmental performance is 0.6.

Experiment 7: reprocessed materials is set at level 3 (5), solid waste is set at level 1 (0.5), energy consumption is set at level 3 (0.16), then the environmental performance is 0.15.

Experiment 8: reprocessed materials is set at level 3 (5), solid waste is set at level 2 (0.7), energy consumption is set at level 1 (0.04), then the environmental performance is 0.6.

Experiment 9: reprocessed materials is set at level 3 (5), solid waste is set at level 3 (0.9), energy consumption is set at level 2 (0.1), then the environmental performance is 0.15.

Taguchi experiments based on FIS results are depicted in Figures 5.12 and 5.13 and the summary of Taguchi experiment results in Table 5.13.

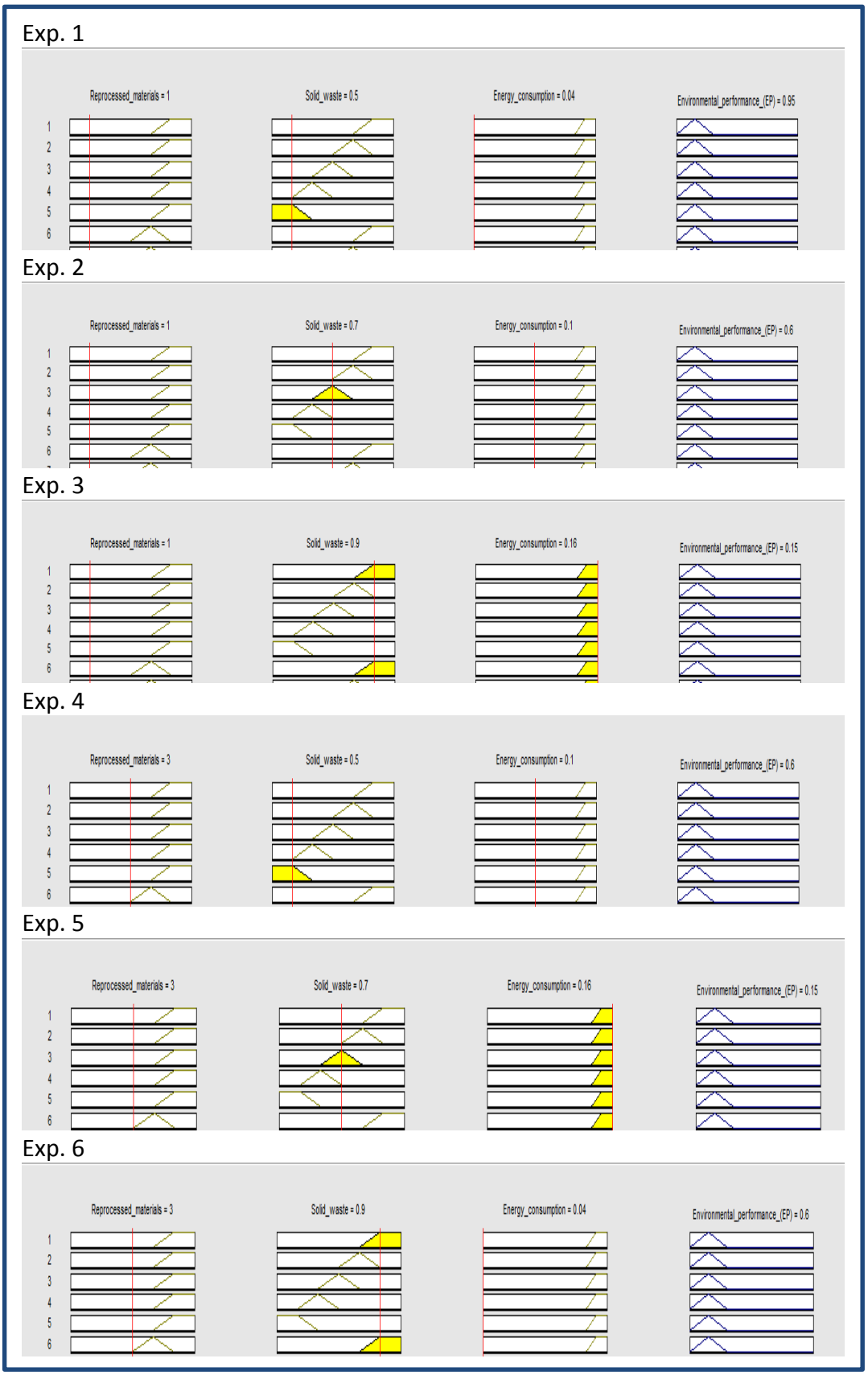


Figure 5.12 Example of Taguchi experiment based from FIS (exp. 1, 2, 3, 4, 5 and 6)

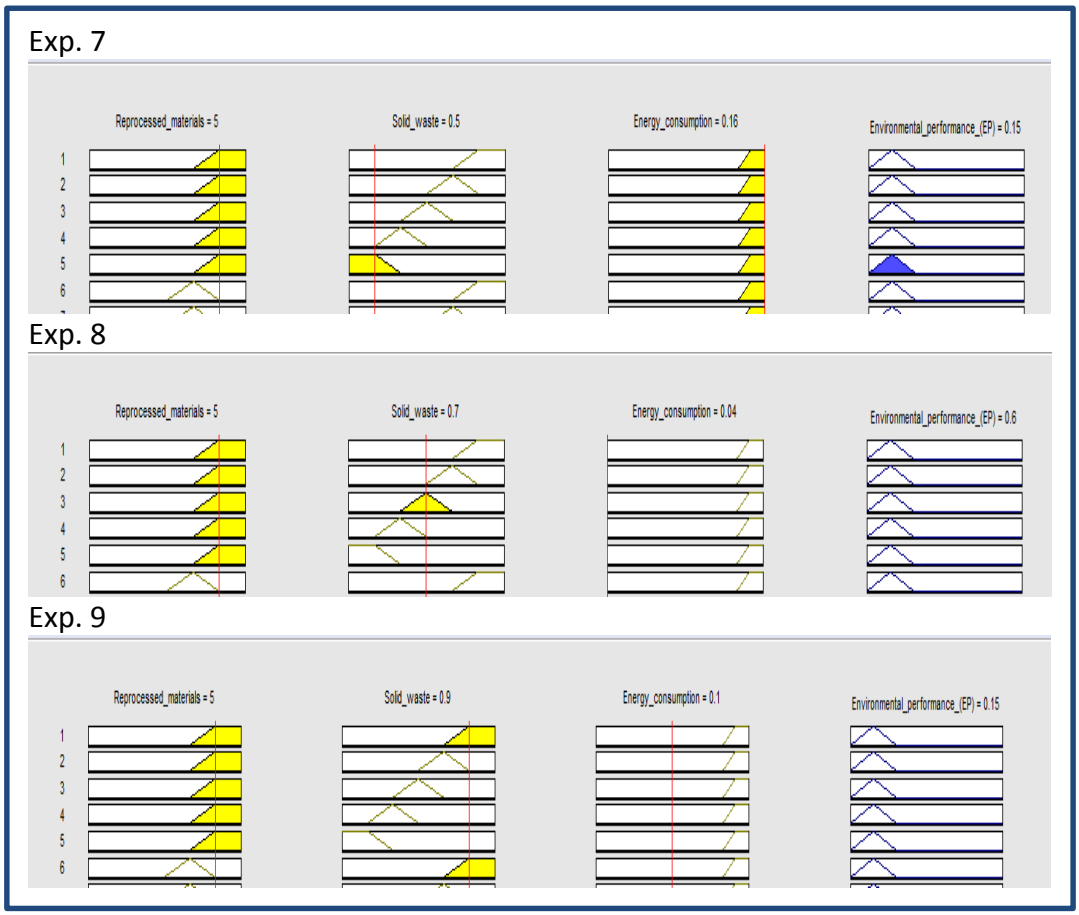


Figure 5.13 Example of Taguchi experiment based from FIS (exp. 7, 8 and 9)

Table 5.13 Taguchi experiment results

N	Reprocessed Materials	Solid Waste	Energy Consumption	EP
1	1	1	1	0.95
2	1	2	2	0.6
3	1	3	3	0.15
4	2	1	2	0.6
5	2	2	3	0.15
6	2	3	1	0.6
7	3	1	3	0.15
8	3	2	1	0.6
9	3	3	2	0.15

d. Analyse the results

At this step the Analysis of Variance is used to determine the order of significance of the factors (environmental indicators). The Taguchi's result consist of three parts namely: analysis for variance for S/N ratio, response table for S/N ratio and the main effect plot

S/N ratio which are depicted in Figures 5.14, 5.15, and 5.16 respectively. Figure 5.14 shows that *energy consumption* has the highest influence while the effect of *solid waste* and *reprocessed materials* are insignificant.

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Reprocessed materials	2	46.44	46.44	23.220	3.23	0.237
Solid waste	2	46.44	46.44	23.220	3.23	0.237
Energy consumption	2	271.80	271.80	135.901	18.88	0.050
Residual Error	2	14.40	14.40	7.200		
Total	8	379.08				

Figure 5.14 ANOVA ratio S/N from MINITAB (confidence level = 0.05)

Signal to noise ratios S/N (*larger the better*), Figure 5.15, the priority of the significance of each factor to environmental performance, shows that *Energy consumption* has the greatest influence on the output variable (environmental performance) followed by (insignificant) *solid waste* and *reprocessed materials* respectively. Response table for S/N ratio also presents the rank of priority of each significant factor to environmental performance (*energy consumption, reprocessed materials*, and *solid waste*). Taguchi results are also graphically shown in Figure 5.16.

Response Table for Signal to Noise Ratios
Larger is better

Level	Reprocessed materials	Solid waste	Energy consumption
1	-7.120	-7.120	-3.106
2	-8.451	-8.451	-8.451
3	-12.464	-12.464	-16.478
Delta	5.344	5.344	13.372
Rank	2.5	2.5	1

Figure 5.15 Responses for S/N from MINITAB

Taguchi method in this step also shows results similar to FIS that energy consumption takes a high priority.

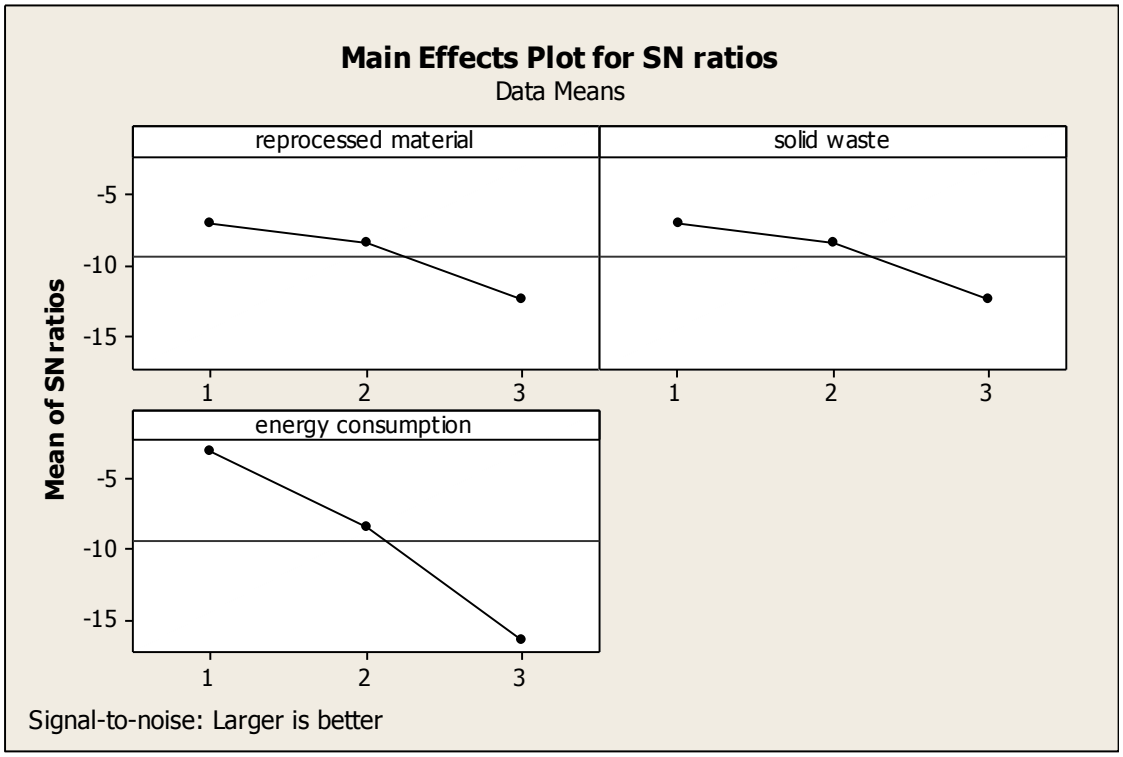


Figure 5.16 Plot ratios for S/N from MINITAB

5.5 Validation of the results via case study

If the results of the application of the model do not meet with the environmental requirements and goals of the company, then the designer should return to the *identify* or *design* stage of the DFSS as the proposed model support the continuous improvement effort and can be run continuously to meet the environmental goal of the company. The validation of the model is illustrated via a real case study in Chapter 6.

5.6 Extended application of environmental performance evaluation model to quality management practice

The concept of quality management refers to the integral framework to achieve and sustain high quality output, focusing on the maintenance and continuous improvement of processes and defect prevention at all levels and all functions of the organisation in order to meet or exceed customer expectations.

Environmental evaluation model is a part of quality management practice. It is flexible enough to be applied to other aspects of quality management as per Figure 5.17 which

indicates that quality performance framework is based on the two main routes for the effect of quality on business performance, namely: the manufacturing route and the market route (Sousa and Voss 2002).

Improvement in internal process quality such as reducing product defects, scrap, re-work including efficiency in using of energy has a significant result in improving operational performance and indicates that this leads to the improvement in business performance. In addition, improvements in product quality also lead to increased sales and larger market share and improvement in product quality in the market route leads to increasing sales and larger market shares or, alternatively, less elastic demand and higher prices.

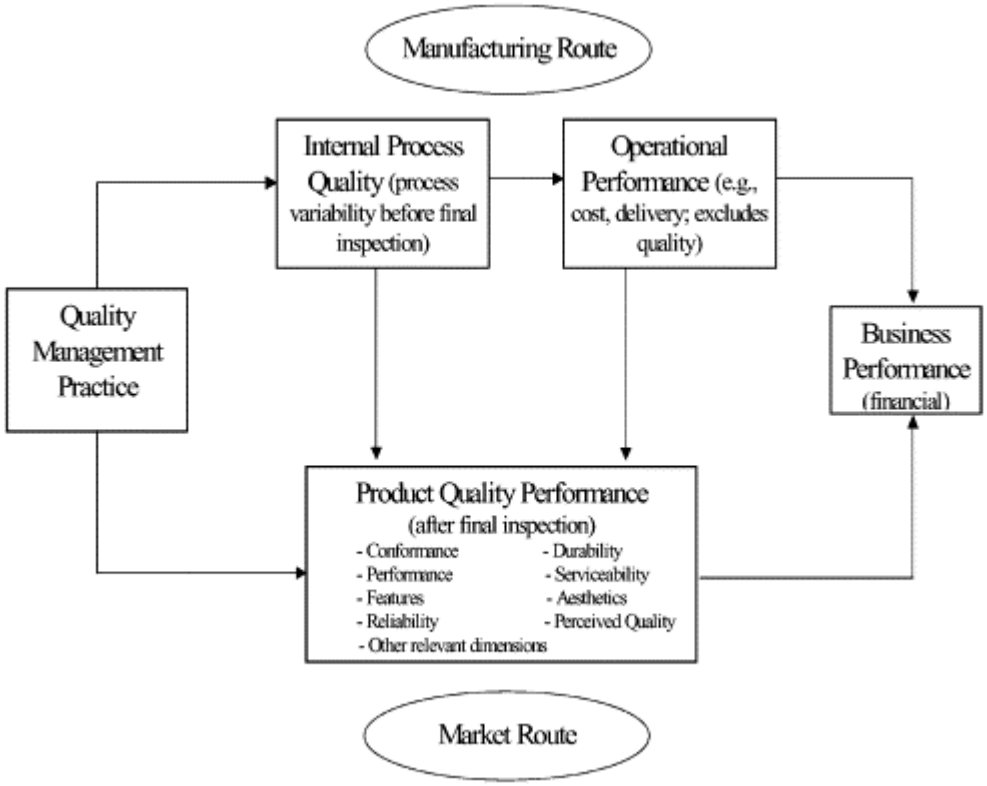


Figure 5.17 The quality performance model by Garvin cited in (Sousa and Voss 2002)

Quality management practice in Figure 5.17 is illustrated in details in Figure 5.18 from which the input variables (indicators) could be defined as e.g., D = product defect, C = manufacturing cost, R = reliability, and M = market share and quality management (QM) as a function of these indicators and introduced as transfer algorithm in EPE model herein.

$$QM = f(D, C, R, M) \tag{5.12}$$



Figure 5.18 The general structure of quality management practice

5.7 The flow chart for the environmental-performance-evaluation model

To further ease understanding and also the application of the proposed EPE model in this chapter, this section illustrates the model in the format of a flow chart which consists of 11 steps as depicted in Figure 5.19 and explained below.

Step 1: Determine environmental requirements and environmental indicators (Section 5.2.1)

Step 2: Translate environmental requirements and indicators into HOQ (Section 5.2.2)
If the fuzzy QFD results are satisfactory and meet the environmental requirements go to the next step, otherwise return to step 1.

Step 3: Define transfer algorithm of environmental performance evaluation (Section 5.3)

Step 4: Develop environmental performance evaluation in fuzzy format (Section 5.4.1)

Step 5: Determine fuzzy membership function (Section 5.4.2)

Step 6: Determine fuzzy rules (Section 5.4.3)

Step 7: Produce results from MATLAB fuzzy logic tool box (Section 5.4.4)
If FIS results meet environment goals go to Step 7, otherwise to Step 5.

Step 8: Define parameter design for Taguchi method (Section 5.4.5 a)

Step 9: Determine level of factor and orthogonal array (Section 5.4.5 b)

Step 10: Run Taguchi's experiments based from FIS result (Section 5.4.5 c)

Step 11: Analyse the results (Section 5.4.5 d)

5.8 Concluding remarks

This chapter described the heart of this research, the construction of a model for environmental performance evaluation, using tools such as DFSS, FIS, QFD, HOQ and Taguchi method to determine the contribution and significance of environmental indicators to environmental performance. The model helps the designers and decision makers of manufacturing companies identify the most problematic environmental indicators and keep them under surveillance and control to minimise the negative environmental impacts of their production. A case study to validate the proposed model into real manufacturing industry is presented in Chapter 6.

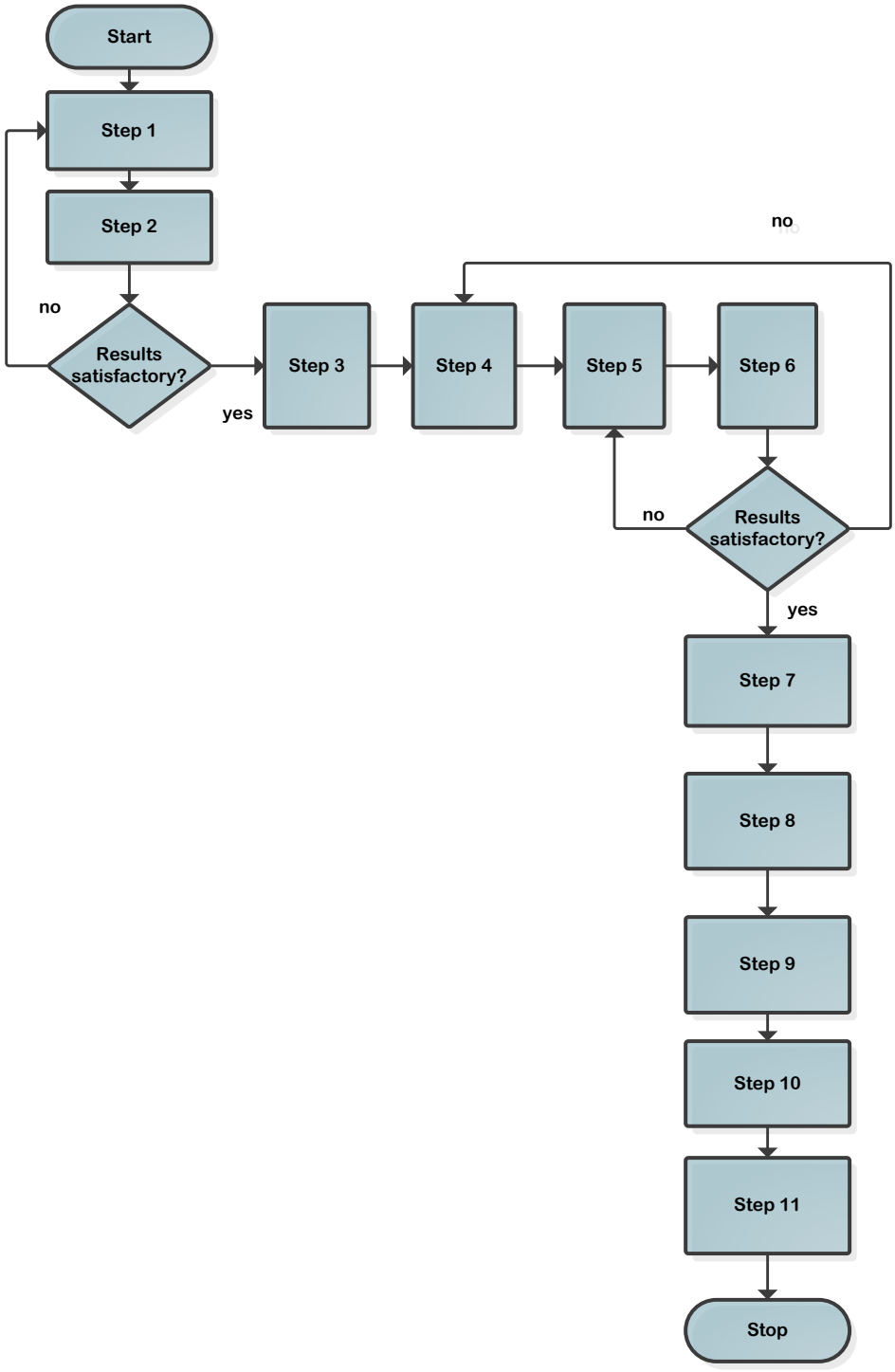


Figure 5.19 The flow chart for applying the proposed model

Chapter Six

Case Study



6.1 Introduction

This chapter demonstrates a case study, application of environmental performance evaluation using DFSS and fuzzy expert system, to verify and validate the proposed model. The proposed model is applied to a manufacturing industry in Indonesia, herein called Company X to comply with their confidentiality requirement. Initially a brief picture of the company is outlined followed by the application of the model. Finally, the results and recommendations are discussed to conclude the chapter.

6.2 Description of case company X (Indonesian textile industry)

There are two main categories for Indonesian textile industry namely integrated textile industry and non-integrated textile industry. Integrated textile industry is a large textile industry which has many types of textile activities such as spinning, weaving, finishing and printing. On the other hand, non-integrated textile industry has only one or two textile activities such as spinning or spinning and weaving.

Company X is a large Indonesian integrated textile company founded in 1974. The production process involves spinning, weaving, finishing, printing and garment operations. This company covers a total of 50 hectares and employs over 8,000 workers and also uses sophisticated machinery. The company's vision is to become an integrated company known for its excellence especially to its shareholders, customers, and employees.

The company's missions are:

- Becoming an integrated textile company that is able to satisfy both its shareholders through its profit and to its customers through excellence in customer service, quality, and price.
- Providing a working environment that focuses on honestly, prudence, safety, and merit-based performance.

6.2.1 Production processes

The classification of textile processes in this company can be divided into two main categories namely dry and wet. *Dry process* is an activity in the textile industry that does not use water during the process while *wet process* is an activity that will use a lot of

water. Spinning and weaving can be categorised as dry processes and finishing and printing can be categorised as a wet process.

Spinning division

Spinning is a process of creating yarn from many types of raw fibre materials. The spinning division produces an average 11,200 tons of yarn per year with three categories of yarn (polyester cotton combed, 100% cotton combed, and 100% cotton carded). This division has three units (*Unit 1* produces export quality yarn, the majority of which is utilised for local and internal company production, *Unit 2* produces superior quality yarn for the international market, and *Unit 3* produces economically priced yarn to meet local market demand). The production capacity in the spinning division is 15,922 bales per annum for Unit 1, 54,616 bales per annum for Unit 2, and 16,406 bales per annum for Unit 3. A brief outline of the spinning flow process is illustrated in Figure 6.1.

Weaving division

Weaving is a process that utilises two different yarns that will be interlaced with each other to form a fabric. The fabric is used for onward production or to be sold to international markets covering Europe, Turkey, and Asia. There are eight categories of fabric produced in this division (polyester cotton combed, 100% cotton combed, 100% cotton carded, polyester rayon, 100% rayon, and plain, twill, oxford). This division has three units and the production capacity for this division is 21,327,465 metre/year for Unit 1, 27,256,740 metre/year for Unit 2, and 36,612,576 metre/year for Unit 3. The flow of the weaving process in this textiles industry is depicted in Figure 6.1.

Finishing and printing division

The main function of the finishing process is to make fabric from the loom or knitting process more attractive and acceptable to the customer. The company has built a reputation as one of the best and biggest batik printing suppliers in the country. Quality products and creative designs are the key factors in the company's success. Product quality is measured from all physical aspects such as colour and fabric strength, easy care, etc. There are three categories of product produced in this division (printing with batik motives, printing with textile motives, and dyed fabric). Production capacity for finishing is 12,480,000 metre/year and 11,136,000 metre/year for printing. A brief flow of the finishing process is illustrated in Figure 6.2.

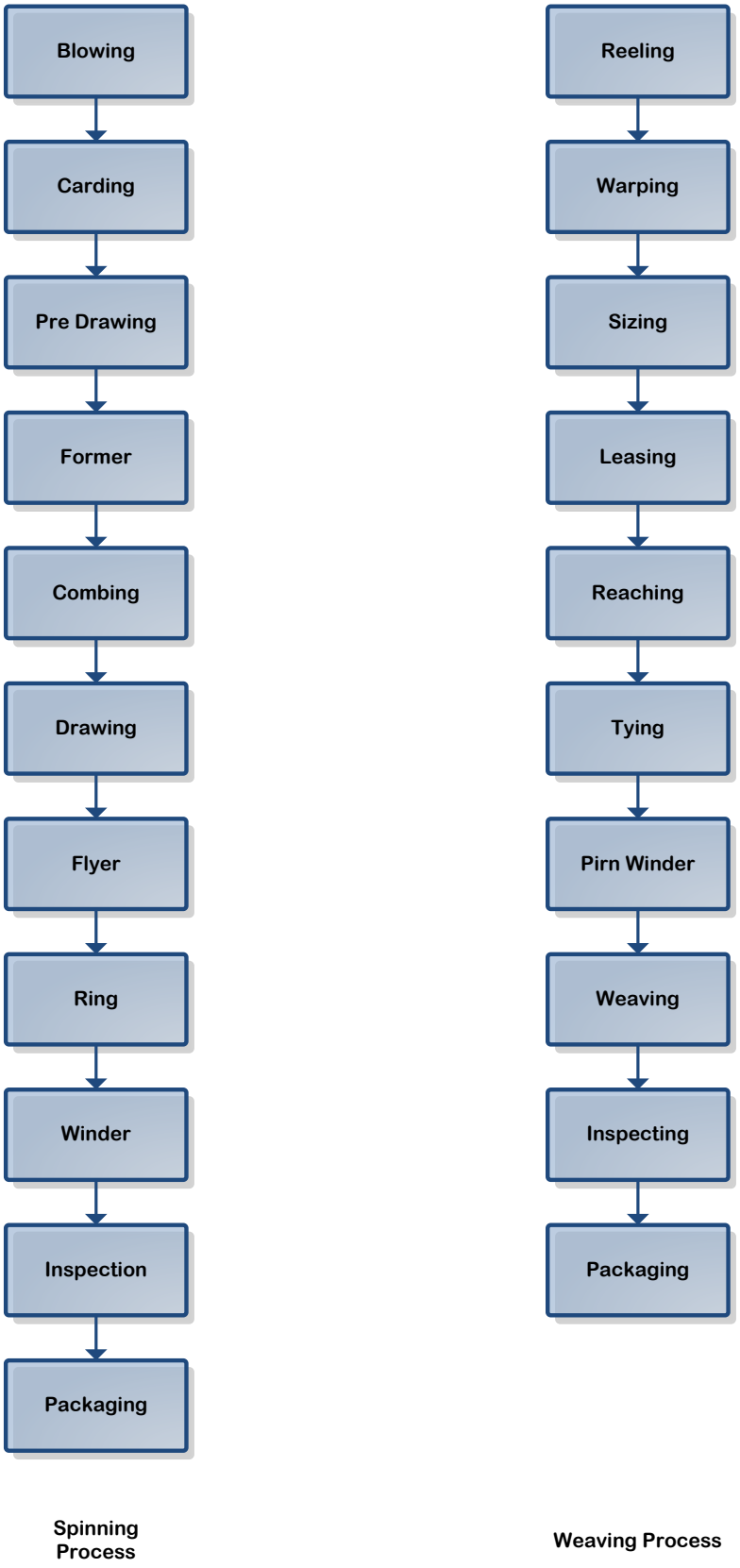


Figure 6.1 Spinning and weaving process

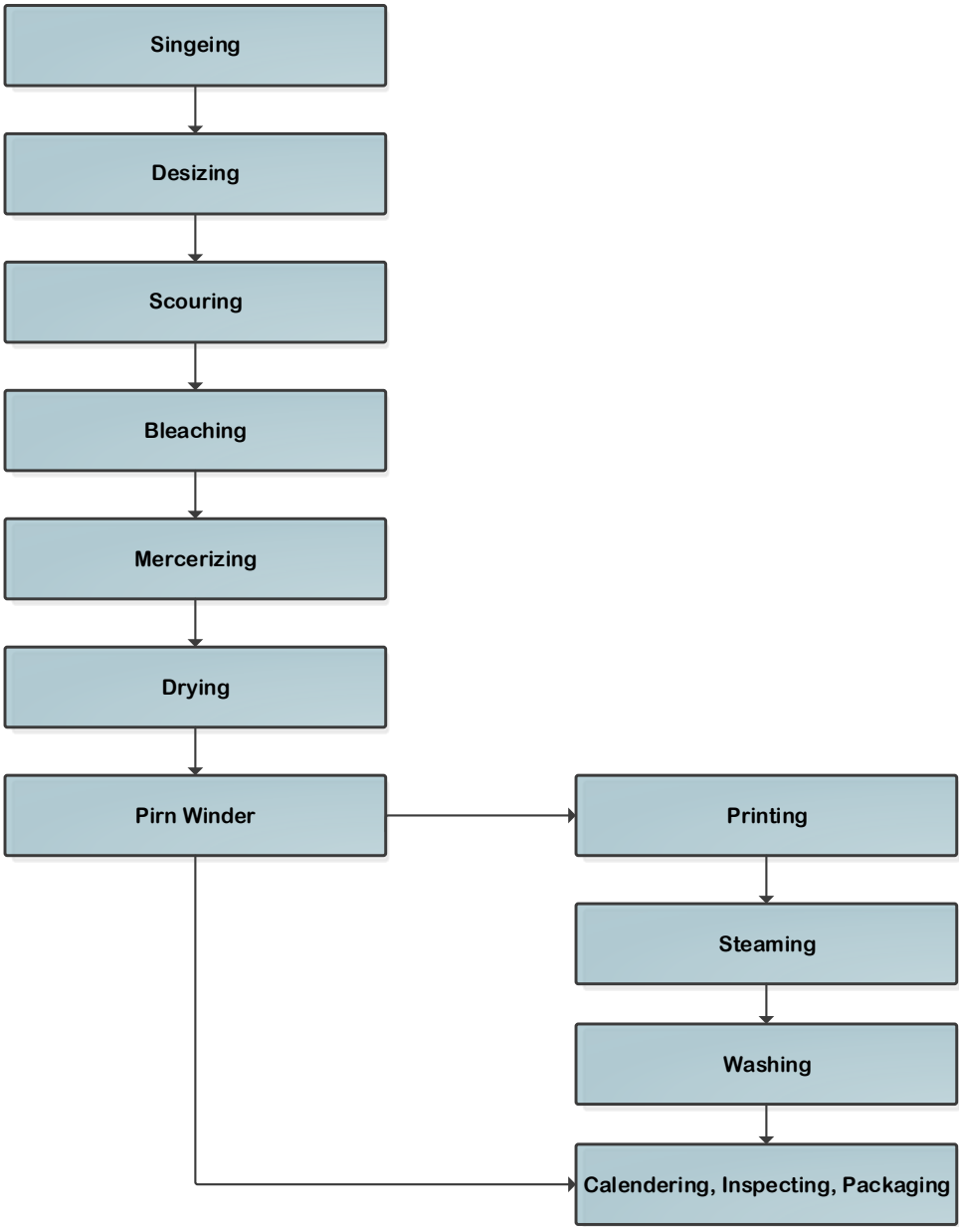


Figure 6.2 Finishing-Printing process

This company also has a garment division which has gained international recognition and currently supplies fabric for international brands and has international markets in Europe, Japan, USA and Australia.

6.2.2 Quality control

To improve the quality of products the company focuses on the two main factors (raw materials and machines) related to sustaining efficiency and energy. The selection of raw materials is important to produce a good product and the company has not compromised in selecting the types of raw materials to provide best product outcome. Also the

preventive maintenance is periodically conducted to ensure that all machines are operating at their optimum levels thus reducing downtime.

In addition, to improve the quality of products, this company has a quality control department in every division (spinning, weaving, finishing-printing and garment). The function of each department is to check, control and to ensure the quality of the output meets the quality standard. The output will be measured and compared with set criteria standards. The industry is concerned on quality improvements and this is shown by the application of several tools and approaches such as control charts and ISO 9000 to improve products and business activities. ISO 9001:2008 has been awarded and implemented in this company to ensure that the entire production process (spinning, weaving, finishing, and garment) are following the standard operating procedure to provide best quality products. Another award that has been achieved by this company is from the Industrial Ministry Award for its proactive renewal of its production machinery. In evaluating business performance on industry the Ministry of Industry uses various parameters including the maintenance and replacement of production machinery, which are keys to maintaining production quality and a safe working environment for employees.

6.2.3 Utility division (wastewater treatment system)

To support environmental awareness and reduce environmental problems, particularly in wastewater pollution, this company has a wastewater treatment system with the main function of ensuring that wastewater from all production processes will be treated to meet government policy and is safe for the environment. The output from this system is checked regularly. The content of dangerous and hazardous materials such as organic carbon (TOC), chemical oxygen demand (COD), biochemical oxygen demand (BOD) and total petroleum hydrocarbons (TPH) is eliminated and achieve a safe level before this wastewater will be discharged into the river (environment).

6.3 Identify company's key performance indicator (KPIs)

To monitor and control the product and processes the company determines KPIs and goals for them are set. Once the product order is received, and while the production process is

running, every outcome of each division is regularly checked. The current KPIs are indicated in table 6.1.

Table 6.1 Current key performance indicators

No.	Indicators	Goal	Responsible	Frequency
1	Product quality	More than 95%	Head of quality control each division	Monthly
2	Product defect	Less than 5%	Head of quality control each division	Monthly
3	Reprocessed materials	Less than 3%	Head of quality control each division	Monthly
4	Solid waste	Less than 0.7%	Head of quality control each division	Monthly
5	Energy consumption	Less than 0,1 KW/unit	Head of quality control each division	Monthly
6	Time delivery	Less than 14 days	Head of quality control each division	Monthly
7	Content of wastewater	Meet with the government standard	Head of unit of utility	Periodically

Even though KPIs are set there is still a gap between current indicators and goals that means the key performance indicators (KPIs) still did not meet with the goal of the organisation. For example, there is still a large percentage of reprocessed materials produced (more than 3%) that means these materials need to be reprocessed. This process possibly has an impact on production time, cost and also influences the delivery time to the customer. Another example is there is still a huge amount of solid waste produced (more than 0.7%) that indicates that this influences the need for raw materials and impacts on the production cost. Even though the organisation's management set the standard for the amount of reprocessed materials and solid waste in each division there is still a large amount of these indicators produced as undesirable output.

Although KPIs are set, and highlighted, it is seen that these KPIs do not included as environmental indicators for environmental performance. Consideration of these indicators could have a great impact on the design of environmentally friendly products.

Although some quality improvement approaches have been used and implemented in the company there is a lack of application of these methods that focus on quality and environment integrally. Currently the only environmental performance consideration in the company is wastewater treatment. Other environmental indicators such as reprocessed materials, solid waste, and energy consumption related to product design and the development process need to be considered and integrated into an environmental performance evaluation process. The environmental indicators need to be set as an improvement target for continuous improvement.

Then the expert team identified seven primary concerns to be considered at company X:

- improve the quality of products;
- reduce product defect;
- reduce the amount of reprocessed material;
- reduce the amount of solid waste;
- reduce energy consumption of products to reduce production cost;
- increase the function of wastewater treatment systems; and
- increase the awareness of environmental problems.

6.4 Application of the developed model to the data from company X

The expert team responsible for environmental performance evaluation involves experts from cross divisional areas at company X who have skill, knowledge and experience related to the production processes, quality control and the environmental evaluation process. The team consists of three managers from three divisions (spinning, weaving, and finishing-printing).

At the company data was collected using interviews, direct observation and literature research. Furthermore a semi structured questionnaire was used as a guidance to direct the conversation during interview with three division managers (as the expert team) to collect information on current key performance indicators, environmental requirements, environmental indicators, and metrics for environmental indicators. The reason for using a semi structured interview was to avoid the rigid interview structure and also to capture any possible information connected with the variables for this research. Questions on a specific topic were posed to the expert team; however they were also given the chance to

express their own ideas and opinions related to the topic. The questionnaire consisted of four groups of questions including company background, production processes, key performance indicators (KPIs) used and environmental performance evaluation.

This case study is divided into two main parts: first is the application of fuzzy QFD with environmental concerns, with the main aim of establishing environmental requirements and environmental indicators, then prioritising environmental indicators; secondly applying the model of environmental performance evaluation using FIS and Taguchi method. Three experts (division managers) were involved to construct HOQ in the QFD approach in the first part. To determine the membership function each environmental indicator is utilised as an input variable and the fuzzy rules applied in the second part, with all experts being involved. These processes have been described in Section 5.7 along with the flow chart for the application of the proposed model (Figure 5.19). This section will follow the flow chart that consists of 11 steps to apply the proposed model to company X.

6.4.1 Step 1: determine environmental requirements and environmental indicators

Environmental requirements and environmental indicators were developed and listed in Section 4.2.1 and 4.2.2. Discussion with the expert team (three division managers) in company X was conducted to determine the company's environmental requirements and environmental indicators. The expert team chooses to initially identify environmental requirements and environmental indicators at the first step of product design and development. The environmental requirements such as less material used, less energy consumption and waste reduction are selected which possibly have a correlation with environmental indicators such as energy consumption, the amount of solid waste, and the amount of reprocessed materials. The expert team expects they can produce products of good quality and also cope with environmental issues for eco-friendly products. After discussions the expert team determined 10 environmental requirements and 10 environmental indicators as depicted in Tables 6.2 and 6.3.

Table 6.2 Selected environmental requirements

No.	Environmental requirements (*ER*)
ER_1	Waste reduction
ER_2	Pollution impact reduction
ER_3	Less material usage
ER_4	Less energy usage
ER_5	Less water usage
ER_6	Easy to process
ER_7	Safer to landfill (safer land pollution)
ER_8	Safer emission (safer air pollution)
ER_9	Less harmful to the living environment
ER_{10}	Disposable

Table 6.3 Selected environmental indicators

No.	Environmental indicators (*EI*)
EI_1	Materials
EI_2	Toxic materials
EI_3	Reprocessed materials
EI_4	Energy consumption
EI_5	Water consumption
EI_6	Air emission
EI_7	Noise/vibration
EI_8	Water pollutant
EI_9	Solid waste
EI_{10}	Wastewater treatment

6.4.2 Step 2: translate environmental requirements and environmental indicators into HOQ

After identifying environmental requirements and environmental indicators the next step is to construct HOQ to prioritise environmental indicators using expert assessment. The fuzzy concept and linguistic terms are used in this step to support the analysis data of QFD approach as explained previously in Chapter 5. The main reason why fuzzy concept is adopted at this stage is to address the subjective and vagueness related to the use of expert judgment during evaluation. By following the algorithm of fuzzy QFD with environmental concerns, explained in Section 5.2 and using Equation 5.1 to 5.9 the weight of environmental requirements $\{w\}$, the relationship between these requirements and environmental indicators $[r]$ and also the value of environmental indicators $\{A\}$ can be calculated.

Three expert team were involved to identify the weight of environmental requirements and relationship between environmental requirements (*ER*) and environmental indicators (*EI*). The calculation of the weight of environmental requirements $\{w\}$ and relationship between environmental requirements and environmental indicators $[r]$ based on expert's opinion can be seen in Appendix 2, 3 and 4. The fuzzy QFD result from experts' opinions is depicted in Tables 6.4.

The HOQ result is depicted in Table 6.5 from which it can be seen the *energy consumption* has the highest level of importance (357.66), followed by *solid waste* (282.93), *the wastewater treatment* (279.53), *reprocessed materials* (257.08), *emission* (218.28), *water pollutant* (208.92), *materials* (204.65), *water consumption* (200.31), *toxicity materials* (145.31) and finally *noise* and *vibration* (118.53). The expert team would focus on the highest scoring such as *energy consumption, solid waste, wastewater treatment,* and *reprocessed materials.*

6.4.3 Step 3: define transfer algorithm of environmental performance evaluation

As described in Section 5.3 (Equation 5.11) that environmental performance is a function of environmental indicators. Then the expert team decided to currently focus only on the top four significant environmental indicators, therefore,

$$EP = f(R, S, E, W) \tag{6.1}$$

Where:

R is reprocessed materials

S is solid waste

E is energy consumption

W is wastewater treatment system

Table 6.4 The fuzzy QFD results from expert's opinion

Environmental req.	**Weight**	***EI₁***			***EI₂***			***EI₃***			***EI₄***			***EI₅***		
Waste reduction	7.58	40.44	48.03	55.61	-	-	-	55.61	63.19	65.72	50.56	58.14	63.19	40.44	48.03	55.61
Pollution impact reduction	7	-	-	-	51.33	58.33	60.67	-	-	-	51.33	58.33	60.67	32.67	39.67	46.67
Less material usage	6.92	50.72	57.64	59.94	-	-	-	46.11	53.03	57.64	36.89	43.81	50.72	-	-	-
Less energy usage	8.17	49	57.17	65.33	-	-	-	59.89	68.06	70.78	65.33	73.5	73.5	-	-	-
Less water usage	5	-	-	-	-	-	-	-	-	-	-	-	-	36.67	41.67	43.33
Easy to process	5.67	37.78	43.44	47.22	-	-	-	30.22	35.89	41.56	30.22	35.89	41.56	-	-	-
Safer to landfill	6.33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Safer emission	6.33	-	-	-	-	-	-	-	-	-	46.44	52.78	54.89	-	-	-
Less harmful to the living environment	6.33	-	-	-	42.22	48.56	52.78	33.78	40.11	46.44	33.78	40.11	46.44	29.56	35.89	42.22
Disposable	6.33	-	-	-	33.78	40.11	46.44	-	-	-	-	-	-	29.56	35.89	42.22

Table 6.4 The fuzzy QFD results from expert's opinion (cont.)

Environmental req.	**Weight**	***EI₆***			***EI₇***			***EI₈***			***EI₉***			***EI₁₀***		
Waste reduction	7.58	35.39	42.97	50.56	35.39	42.97	50.56	40.44	48.03	55.61	55.61	63.19	65.72	50.56	58.14	63.19
Pollution impact reduction	7	32.67	39.67	46.67	32.67	39.67	46.67	42	49	56	37.33	44.33	51.33	51.33	58.33	60.67
Less material usage	6.92	-	-	-	-	-	-	-	-	-	41.5	48.42	55.33	-	-	-
Less energy usage	8.17	43.56	51.72	59.89	-	-	-	-	-	-	-	-	-	-	-	-
Less water usage	5	-	-	-	-	-	-	26.67	31.67	36.67	-	-	-	36.67	41.67	43.33
Easy to process	5.67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Safer to landfill	6.33	-	-	-	-	-	-	-	-	-	42.22	48.56	52.78	29.56	35.89	42.22
Safer emission	6.33	42.22	48.56	52.78	-	-	-	-	-	-	-	-	-	-	-	-
Less harmful to the living environment	6.33	29.56	35.89	42.22	29.56	35.89	42.22	33.78	40.11	46.44	33.78	40.11	46.44	33.78	40.11	46.44
Disposable	6.33	-	-	-	-	-	-	33.78	40.11	46.44	33.78	40.11	46.44	42.22	48.56	52.78

Table 6.5 The HOQ result

	Environmental requirements	**Weight**	***EI*$_1$**	***EI*$_2$**	***EI*$_3$**	***EI*$_4$**	***EI*$_5$**	***EI*$_6$**	***EI*$_7$**	***EI*$_8$**	***EI*$_9$**	***EI*$_{10}$**
ER$_1$	Waste reduction	7.58	48.03	-	61.93	57.51	48.03	42.97	42.97	48.03	61.93	57.51
ER$_2$	Pollution impact reduction	7.00	-	57.17	-	57.17	39.67	39.67	39.67	49.00	44.33	57.17
ER$_3$	Less material usage	6.92	56.49	-	52.45	43.81	-	-	-	-	48.42	-
ER$_4$	Less energy usage	8.17	57.17	-	66.69	71.46	-	51.72	-	-	-	-
ER$_5$	Less water usage	5.00	-	-	-	-	40.83	-	-	31.67	-	40.83
ER$_6$	Easy to process	5.67	42.97	-	35.89	35.89	-	-	-	-	-	-
ER$_7$	Safer to landfill	6.33	-	-	-	-	-	-	-	-	48.03	35.89
ER$_8$	Safer emission	6.33	-	-	-	51.72	-	48.03	-	-	-	-
ER$_9$	Less harmful to the living environment	6.33	-	48.03	40.11	40.11	35.89	35.89	35.89	40.11	40.11	40.11
ER$_{10}$	Disposable	6.33	-	40.11	-	-	35.89	-	-	40.11	40.11	48.03
	Total A_j		**204.65**	**145.31**	**257.08**	**357.66**	**200.31**	**218.28**	**118.53**	**208.92**	**282.93**	**279.53**
	Percentage of A_j		**9.00**	**6.39**	**11.31**	**15.73**	**8.81**	**9.60**	**5.21**	**9.19**	**12.45**	**12.30**
	Rank		**7**	**9**	**4**	**1**	**8**	**5**	**10**	**6**	**2**	**3**

6.4.4 Step 4: develop environmental performance evaluation in fuzzy format

In this step, FIS from MATLAB fuzzy logic tool box is employed to determine the environmental evaluation function, called Transfer Function according to MATLAB terminology. The output from MATLAB, Figure 6.3, depicts input and output variables along with transfer function.

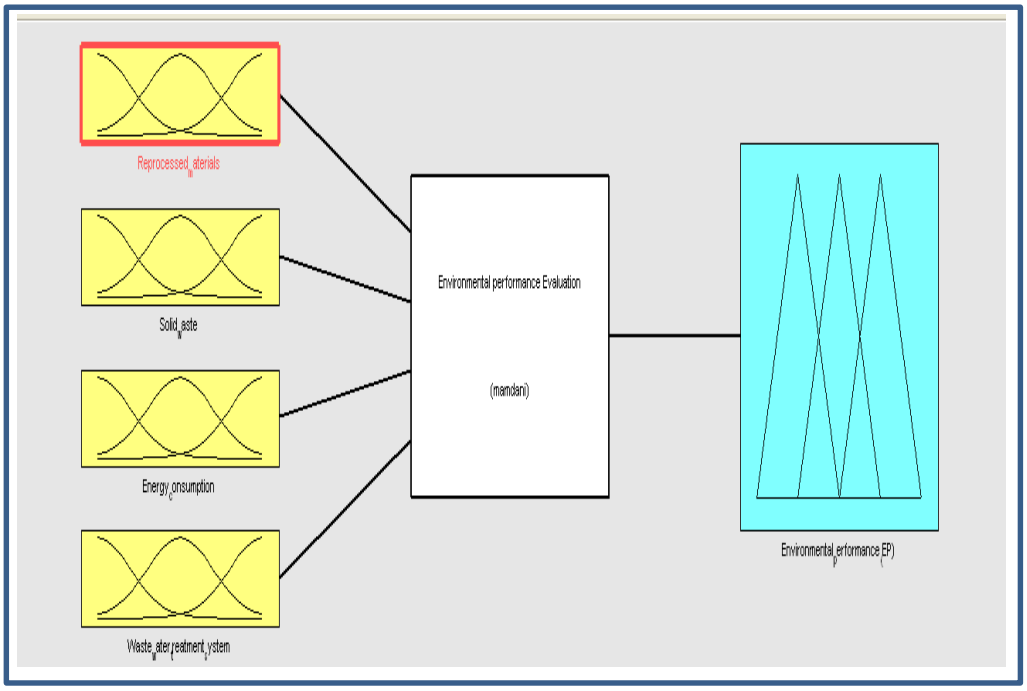


Figure 6.3 Input and output variables in fuzzy format

6.4.5 Step 5: determine fuzzy membership function

As described previously, four environmental indicators are selected for this case study. The identification of membership function of reprocessed materials, solid waste and energy consumption has been explained in Section 5.4.2. In Indonesian textile industry the wastewater treatment system is important and influences environmental performance. This system is periodically assessed to make sure the content of wastewater reaches a safe level for the environment. Wastewater treatment system is measured according to the government's rule and conducted periodically by a government agent who checks and measures the contamination in wastewater, such as the amount of BOD, COD, the level of PH, etc. The government has set five level of wastewater contamination for Indonesian textile industry namely: black, red, blue, green and gold as follows:

- *Black* indicates that industry still does not have a wastewater treatment system.

- *Red* indicates that industry has wastewater treatment systems but the result still does not meet the government standard.
- *Blue* indicates that industry has wastewater treatment systems and the results meet the government standard.
- *Green* indicates industry implements reusing treated wastewater.
- *Gold* indicates the industry achieves satisfactorily purifies wastewater.

Based on the above-mentioned classification the expert team interpreted the environmental performance of wastewater, in conjunction with fuzzy membership function, from *very poor* to *very good* as per Table 6.6. The fuzzy membership function for wastewater treatment system can be seen in Figure 6.4.

Table 6.6 Linguistic terms and measurement for wastewater treatment system

Linguistic Terms	**Fuzzy number**	**Degree of wastewater treatment**
very poor	(1,1,2)	Black
Poor	(1,2,3)	Red
Fair	(2,3,4)	Blue
Good	(3.4.5)	Green
very good	(4,5,5)	Gold

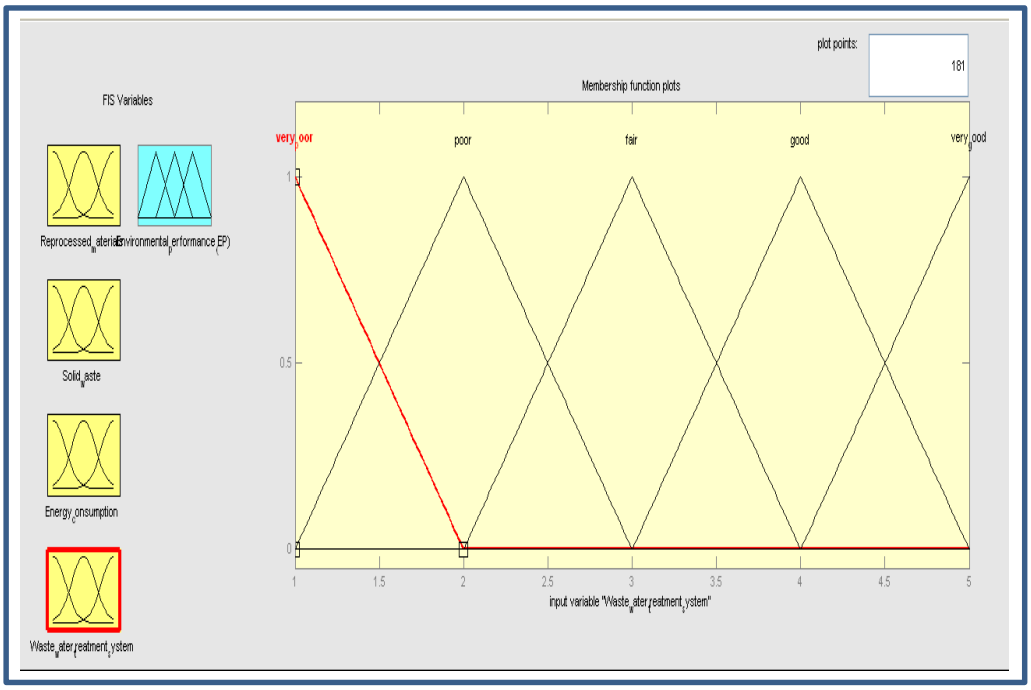


Figure 6.4 Fuzzy membership function for wastewater treatment from MATLAB

Environmental performance (Output)

The membership function of output variable and linguistic terms are depicted in Table 6.7 and Figure 6.5. From which it can be seen that both *very poor* and *poor* condition need immediate attention for improvement. A range of output between 0.91 and 1 indicates that the achievement of environmental performance fulfils the environmental performance criterion. Obviously, the environmental evaluation process and environmental indicators should be continuously monitored and maintained.

Table 6.7 Range of environmental performance and linguistic value (output)

Linguistic Terms	Value
Optimum	0.91-1.0
Satisfied	0.71-0.90
Moderate	0.51-0.70
Poor	0.31-0.50
Very Poor	0.00- 0.30

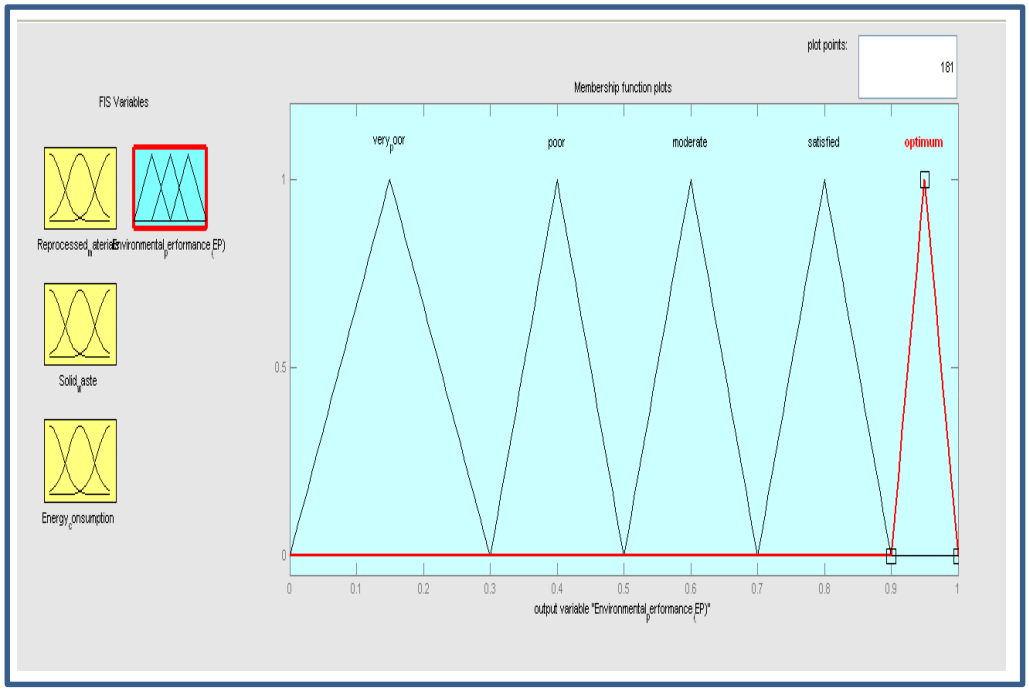


Figure 6.5 Membership function for output variable

6.4.6 Step 6: determine fuzzy rules

Table 6.8 shows the sample of *if then* rules. These rules are determined via the expert's knowledge of cross functionality at company X (including spinning, weaving and finishing-printing divisions).

Table 6.8 The samples of *if then* rules

Wastewater treatment system very good					
Energy consumption high					
Solid Waste \ Reprocessed Materials	Very High	High	Medium	Low	Very Low
Very High	Poor	Poor	Moderate	Moderate	Moderate
High	Poor	Poor	Moderate	Moderate	Moderate
Medium	Poor	Poor	Moderate	Moderate	Moderate
Low	Poor	Poor	Moderate	Moderate	Moderate
Very Low	Poor	Poor	Moderate	Moderate	Moderate
Energy consumption medium					
Solid Waste \ Reprocessed Materials	Very High	High	Medium	Low	Very Low
Very High	Poor	Poor	Poor	Moderate	Moderate
High	Poor	Poor	Poor	Moderate	Moderate
Medium	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Low	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Very Low	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Energy consumption low					
Solid Waste \ Reprocessed Materials	Very High	High	Medium	Low	Very Low
Very High	Moderate	Moderate	Satisfied	Satisfied	Satisfied
High	Moderate	Moderate	Satisfied	Satisfied	Satisfied
Medium	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied
Low	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied
Very Low	Satisfied	Satisfied	Satisfied	Satisfied	Optimum

The number of membership function of each variable will significantly influence the number of these rules. Samples of rule viewer from FIS are depicted in Figure 6.6.

The expert team determines the range of membership function of each environmental indicator as an input variable and the upper and lower specification limits for each range were determined. The membership function for each indicator varies from one to five (5 for reprocessed materials, 5 for solid waste, 3 for energy consumption, and 5 for

wastewater treatment system). The number of fuzzy rules in this case is 375 rules. Figure 6.6. shows, as an example, that if the value of reprocessed materials, solid waste, energy consumption and wastewater treatment system are 3, 0.7, 0.04, 4 respectively, then the environmental performance is 0.8 (rule number 288).

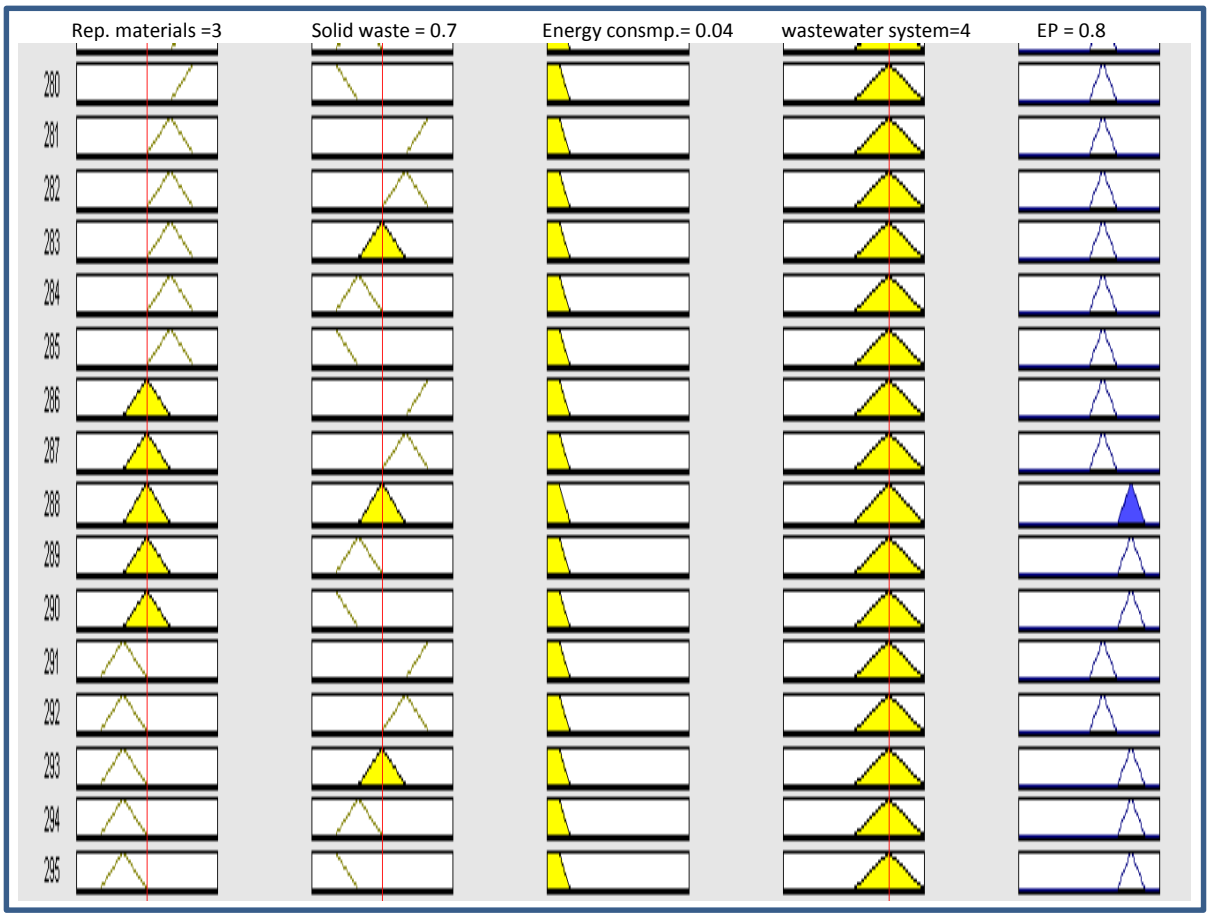


Figure 6.6 The sample rules viewer from FIS

6.4.7 Step 7: produce results from MATLAB fuzzy logic tool box

Fuzzy solution results from FIS are presented as a response surface. The value of each input variable can be set and the output response can be calculated as a score that will be transformed into linguistic terms. There are six response surface graphs to represent the environmental performance as a function of two environmental indicators namely: reprocessed materials and solid waste, reprocessed materials and energy consumption, reprocessed materials and wastewater treatment system, solid waste and energy consumption, solid waste and wastewater treatments system, and energy consumption and wastewater treatment system as depicted in Figures 6.7 to 6.12.

Figure 6.7 presents the influence of wastewater treatment system and energy consumption on the environmental performance where it can be seen that the influence of both indicators are similar.

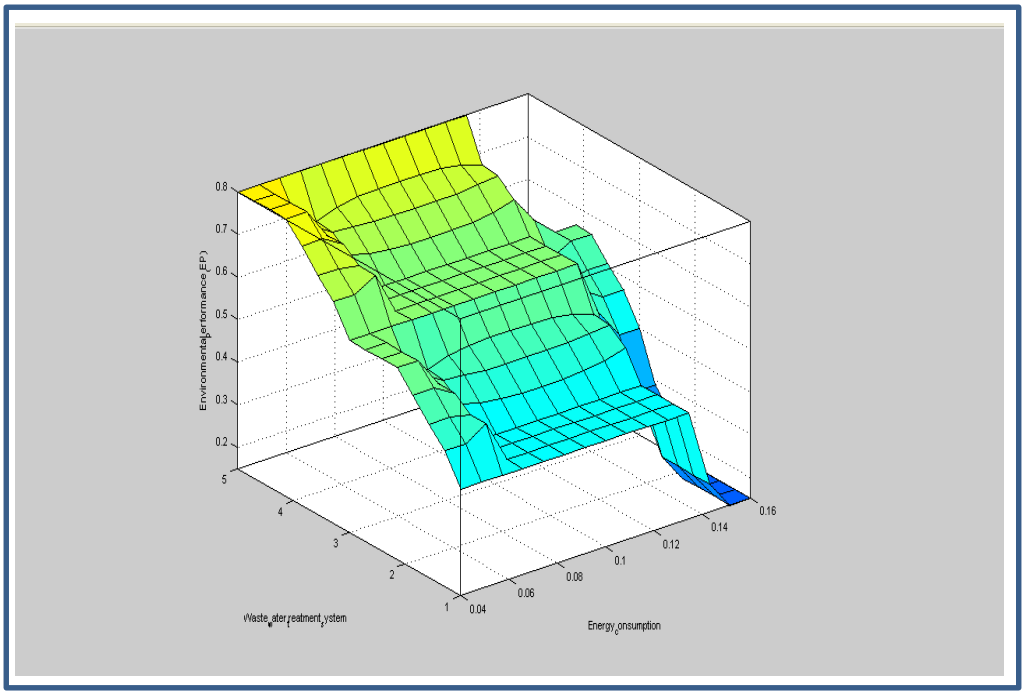


Figure 6.7 Influence of wastewater treatment system and energy consumption on environmental performance

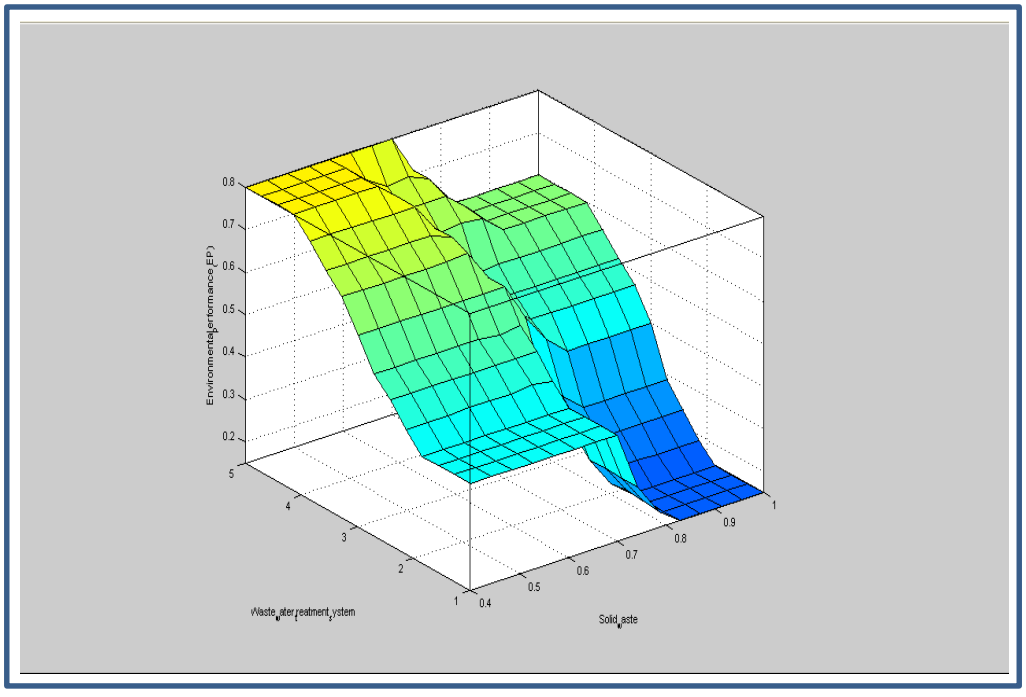


Figure 6.8 Influence of wastewater treatment system and solid waste on environmental performance

Figure 6.8 presents the influence of wastewater treatment system and solid waste on the environmental performance where it can be seen that wastewater treatment system has a far more significant influence on the environmental performance than solid waste.

Figure 6.9 presents the influence of wastewater treatment system and reprocessed materials on the environmental performance where it can be seen that wastewater treatment system is far more influential than reprocessed materials.

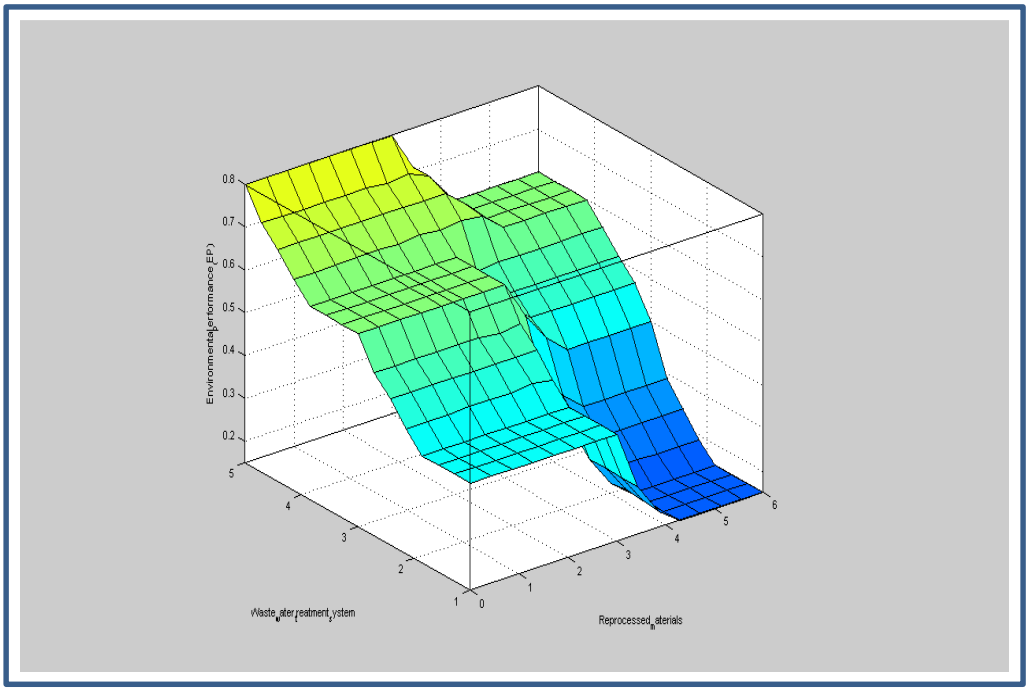


Figure 6.9 Influence of wastewater treatment system and reprocessed materials on environmental performance

Figure 6.10 presents the influence of the solid waste and reprocessed materials on the environmental performance where it can be seen that solid waste is much more influential than reprocessed materials.

Figure 6.11 presents the influence of reprocessed materials and energy consumption on the environmental performance where it can be seen that energy consumption is much more influential than reprocessed materials.

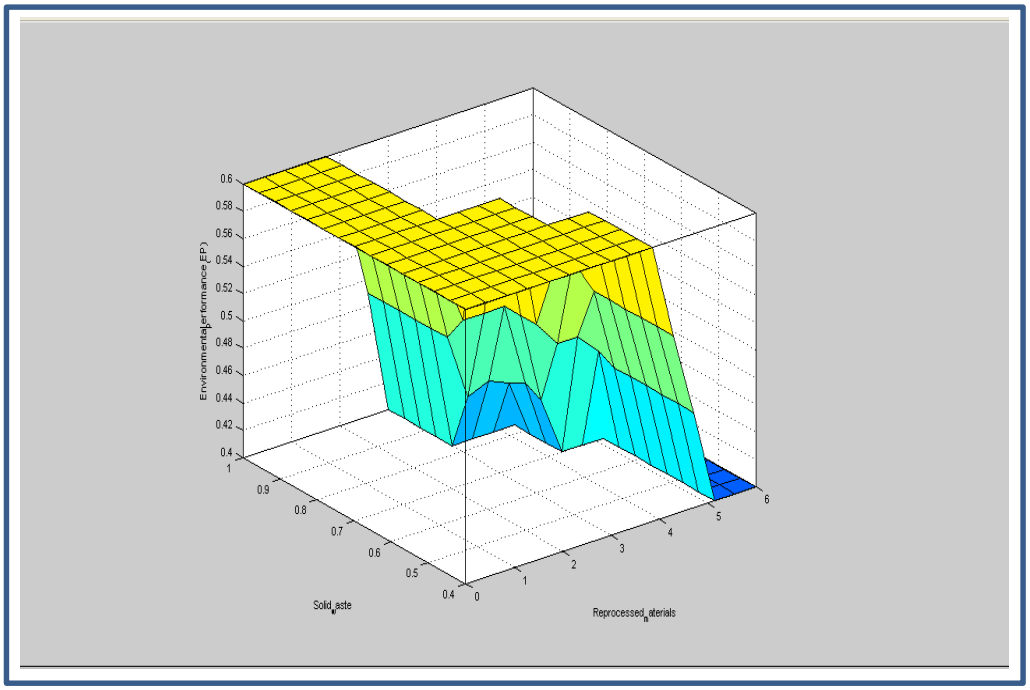


Figure 6.10 Influence of solid waste and reprocessed material on environmental performance

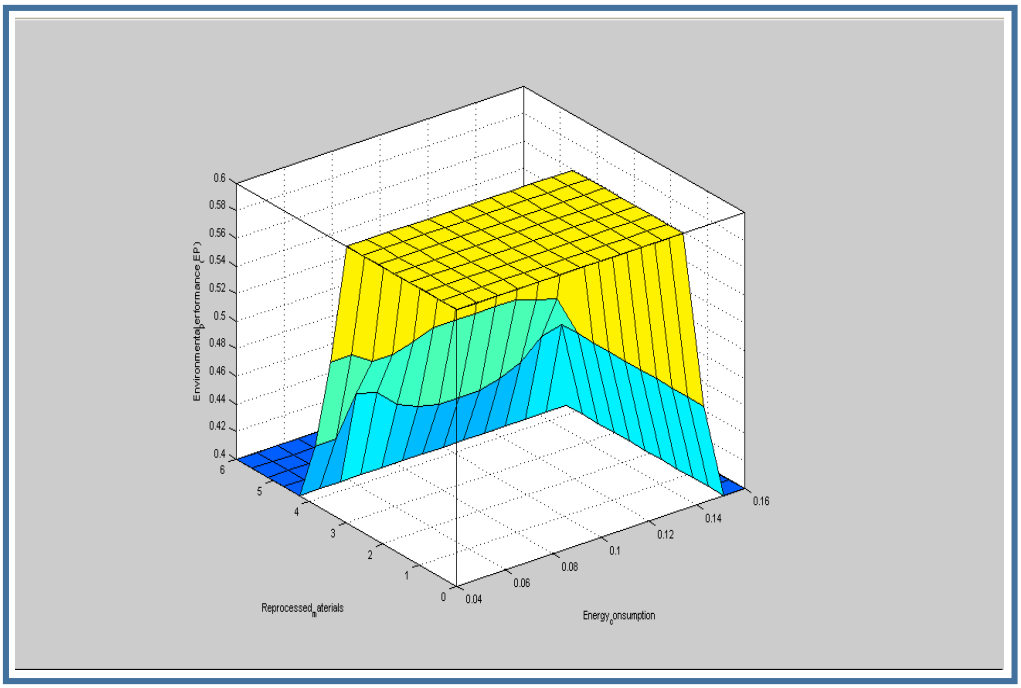


Figure 6.11 Influence of reprocessed materials and energy consumption on environmental performance

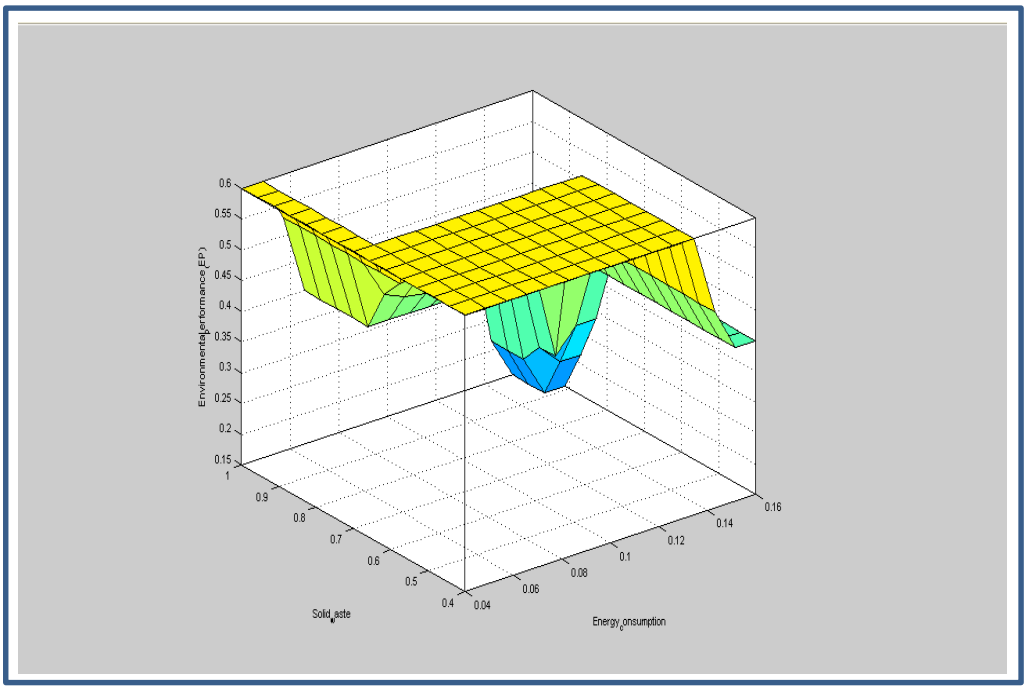


Figure 6.12 Influence of solid waste and energy consumption on environmental performance

Figure 6.12 presents the influence of solid waste and energy consumption on the environmental performance where it can be seen that energy consumption is more influential than solid waste. While solid waste has a lesser effect on the environmental performance any decrease or increase on energy consumption significantly impacts on the output variable.

6.4.8 Step 8: define parameter design for Taguchi method

As explained in Section 5.4.5 to analyse the main effect of environmental indicators (input variables) on environmental performance (output variable) from FIS result, Taguchi method is conducted. The result of this method determines the order of significance of selected environmental indicators (energy consumption, wastewater treatment, solid waste and reprocessed materials). These indicators are used as parameters in design of Taguchi's experiment followed by identification of level of factor for each variable and orthogonal array. The output variable is environmental performance and the quality characteristic for the output variable is *larger the better (LTB).*

6.4.9 Step 9: determine level factors and orthogonal array

Based on the fuzzy solution result from FIS, there are four environmental indicators as controllable factors (energy consumption, wastewater treatment, solid waste and reprocessed materials). Once established the expert team determines the level of factor of parameter design with three levels (namely *low*, *medium* and *high*) for each of them as shown in Table 6.9. The orthogonal array $L_{27}(3^4)$ is selected as shown in Columns 1 to 4 of Table 6.10.

Table 6.9 Level of factor experiment

Factors	level 1	level 2	level 3
Reprocessed materials	Low (1)	Medium (3)	High (5)
Solid waste	Low (0.5)	Medium (0.7)	High (0.9)
Energy consumption	Low (0.04)	Medium (0.1)	High (0.16)
Wastewater treatment system	Low (2)	Medium (3)	High (4)

6.4.10 Step 10: run Taguchi's experiments based from FIS result

After the expert team determines level of factor and orthogonal array to conduct Taguchi's experiments, then experiments will be conducted based on FIS result. The experiment result from Taguchi is depicted in Table 6.10. The sample of Taguchi experiments based on FIS results are depicted in Figures 6.13 and 6.14. For illustrative example, there are 8 experiments (experiment 1, 2, 3, 5, 13, 14, 15 and 20) from FIS result and explained below.

Experiment 1: reprocessed materials is set at level 1 (1), solid waste is set at level 1 (0.5), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 1 (2), then the environmental performance is 0.6.

Experiment 2: reprocessed materials is set at level 1 (1), solid waste is set at level 1 (0.5), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 2 (3), then the environmental performance is 0.6.

Experiment 3: reprocessed materials is set at level 1 (1), solid waste is set at level 1 (0.5), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 3 (4), then the environmental performance is 0.8.

Experiment 5: reprocessed materials is set at level 1 (1), solid waste is set at level 2 (0.7), energy consumption is set at level 2 (0.1), and wastewater treatment system is set at level 2 (3), then the environmental performance is 0.6.

Table 6.10 Experiment result

n	Reprocessed materials	Solid waste	Energy consumption	Wastewater system	EP
1	1	1	1	1	0.6
2	1	1	1	2	0.6
3	1	1	1	3	0.8
4	1	2	2	1	0.4
5	1	2	2	2	0.6
6	1	2	2	3	0.6
7	1	3	3	1	0.15
8	1	3	3	2	0.15
9	1	3	3	3	0.4
10	2	1	3	3	0.6
11	2	1	3	1	0.15
12	2	1	3	2	0.4
13	2	2	1	3	0.8
14	2	2	1	1	0.6
15	2	2	1	2	0.6
16	2	3	2	3	0.6
17	2	3	2	1	0.15
18	2	3	2	2	0.4
19	3	1	2	2	0.4
20	3	1	2	3	0.6
21	3	1	2	1	0.15
22	3	2	3	2	0.4
23	3	2	3	3	0.4
24	3	2	3	1	0.15
25	3	3	1	2	0.4
26	3	3	1	3	0.6
27	3	3	1	1	0.4

Experiment 13: reprocessed materials is set at level 2 (3), solid waste is set at level 2 (0.7), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 3 (4), then the environmental performance is 0.8.

Experiment 14: reprocessed materials is set at level 2 (3), solid waste is set at level 2 (0.7), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 1 (2), then the environmental performance is 0.6.

Experiment 15: reprocessed materials is set at level 2 (3), solid waste is set at level 2 (0.7), energy consumption is set at level 1 (0.04), and wastewater treatment system is set at level 2 (3), then the environmental performance is 0.6.

Experiment 20: reprocessed materials is set at level 3 (5), solid waste is set at level 1 (0.5), energy consumption is set at level 2 (0.1), and wastewater treatment system is set at level 3 (4), then the environmental performance is 0.6.



Figure 6.13 Example of Taguchi experiment based from FIS (exp. 1, 2 and 3)



Figure 6.14 The sample of Taguchi experiment based from FIS (exp.5, 13, 14, 15 and 20)

6.4.11 Step 11: analyse the results

The Taguchi results consist of three parts namely: analysis of variance (ANOVA) of S/N ratio, response table for signal to noise ratio (*larger the better*) and main effect plot for S/N ratio depicted in Figures 6.15, to 6.17 respectively. The first part of Taguchi results is ANOVA, if the P value of each indicator is less than or equal to the confidence level (here 0.05) the null hypothesis is rejected and concluded that the factor has a significant impact on the output variable. Figure 6.15 shows that *wastewater treatment system* and *energy consumption* have the highest environmental impact followed by *solid waste*; while the effect of *reprocessed materials* is insignificant.

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
reprocessed material	2	12.64	12.64	6.321	0.91	0.421
solid waste	2	53.50	53.50	26.752	3.84	0.041
energy consumption	2	201.84	201.84	100.919	14.48	0.000
waste water system	2	238.04	238.04	119.022	17.08	0.000
Residual Error	18	125.43	125.43	6.968		
Total	26	631.46				

Figure 6.15 ANOVA for S/N ratio (from MINITAB)

The second part of Taguchi's experiment results is signal to noise ratios S/N (*larger the better*). Figure 6.16, shows the priority of the significance of each factor to environmental performance. *Wastewater treatment system* has the greatest influence on the output variable (environmental performance) followed by *energy consumption, solid waste*, and (insignificant) *reprocessed materials* respectively. Response table for S/N ratio also presents the rank of priority of each significant factor to environmental performance (*wastewater treatment system, energy consumption, solid waste* and *reprocessed materials*).

Response Table for Signal to Noise Ratios
Larger is better

Level	reprocessed material	solid waste	energy consumption	wastewater system
1	-7.618	-7.618	-4.664	-11.909
2	-7.618	-6.671	-8.287	-7.731
3	-9.069	-10.016	-11.354	-4.664
Delta	1.452	3.345	6.690	7.245
Rank	4	3	2	1

Figure 6.16 Response table for S/N ratio (from MINITAB)

Taguchi's experiment results are also shown in graphical format. The main effect plot S/N ratio is depicted in Figure 6.17 where, similar to the results of Anova, it can be seen that both *wastewater treatment systems* and *energy consumption* have the greatest impact to the output variable.

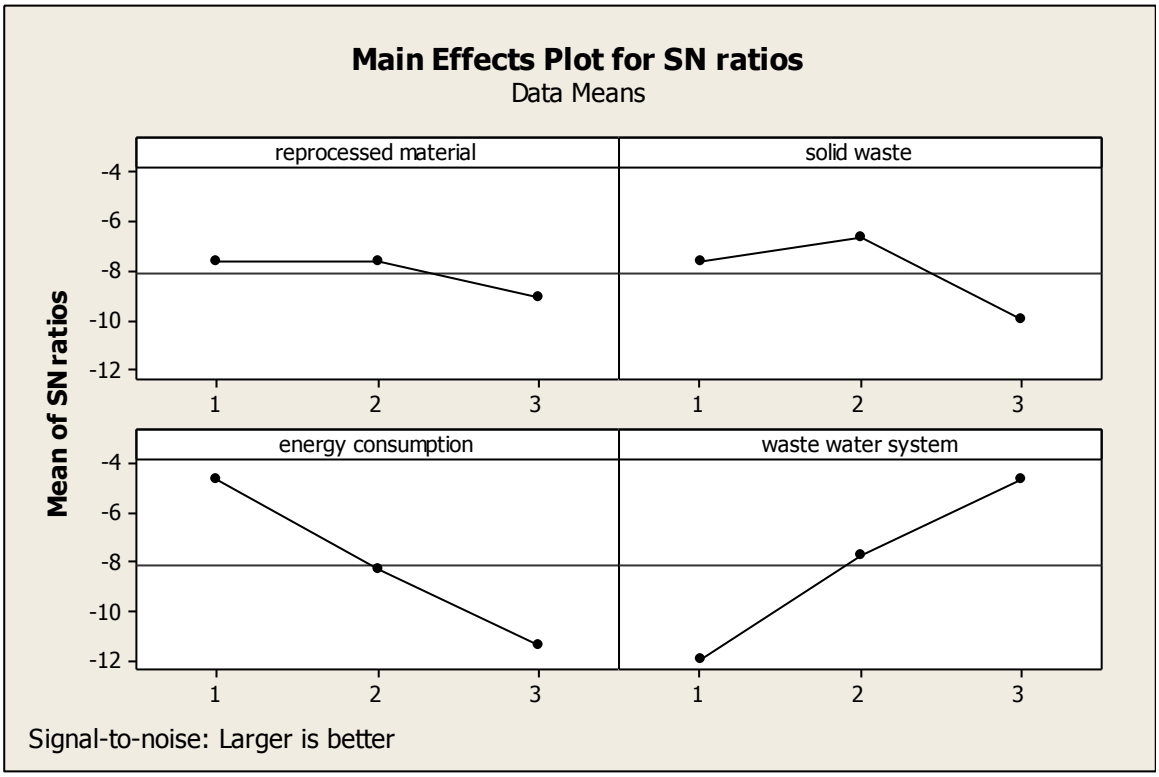


Figure 6.17 Main effects plot for S/N ratio

The three significant indicators specified in Figure 6.17 are to be set as target for continuous improvement of the company's performance. However, if limitations on the company's resources prohibits them to improve all three indicators, they can concentrate on improving the most significant ones, namely *wastewater treatment system* and *energy consumption*.

6.5 Findings and recommendations to company X

Regarding the company's impact on the environment they are currently giving consideration to the wastewater treatment system only with no clear understanding of the degree of the effect of the identified KPIs on their environmental performance; also no effort towards the integration of the measurement of environmental performance into product design and development involving KPIs.

A long-term and meaningful EPE process and environmental improvement require the involvement and cooperation of all employees of the organisation. Expert team on environmental evaluation must be established and communications with all employees need to be conducted on a routine basis, for example using suggestion boxes, meetings and committees. Some of the employees may have useful suggestions on minimising the negative environmental impacts.

Although green manufacturing and environmentally friendly product design are recognised widely to address environmental issues, unfortunately, little attention has been paid to address environmental practical problems in industry via EPE model. In comparison to other environmental performance evaluations, the DFSS methodology can provide a set of appropriate environmental indicators related to design of environmentally friendly products which considers environmental requirements at the first step of product design and development. This provides more accurate evaluation which can be used to improve a specific improvement due to organisational environmental goals and circumstances. The application of DFSS algorithm from six sigma methodology is useful to create the design of environmental performance evaluation. Environmental performance as a function of environmental indicators is to address the variability of the four selected environmental indicators namely: reprocessed materials, solid waste, energy consumption, and wastewater treatment. The input from the experts on the expert team can determine measures which are relevant and appropriate with the company's circumstances and conditions. Based on their knowledge, skill, and experience in the company, they can determine these measures and by using common sense, human thinking and judgment as expert team members.

Even though company X have applied and implemented several continuous improvement methods into its business activities through identifying key performance indicators its goal (supported by monitoring and controlling of the quality system including wastewater treatment system), that highlights a huge amount of environmental indicators such as reprocessed materials, solid waste and energy consumption were still found that impacts on quality performance, such as cost and time, and finally has a great impact on customer satisfaction. The model also outlined how to determine and prioritise environmental indicators related to product design and development processes to provide products that meet environmental requirements which was not previously addressed. This case study

demonstrated how the model is very useful and has great flexibility for improving environmental performance and also supporting continuous improvement efforts.

The flexibility of the model lies in that it can accommodate many categories of environmental performance indicators such as *EMIs*, *ECIs*, and *EPIs* and also it can be integrated with other quality indicators such as quality, cost and time to furnish competitive performance. The proposed model can also be further developed associated with the environmental business goals.

Even though the case study is demonstrated in a textile industry, the proposed model is flexible enough to be adopted and modified for other applications. In some cases, the range of membership function for each indicators and output performance can be customised to the necessities of the company. Furthermore, the model is flexible enough to include more environmental indicators and do corresponding adjustments to its fuzzy membership function and rules.

This case study also demonstrated how the model can determine measurements which can be used to improve quality and evaluate environmental performance, environmental goals, and business performance. Finally, if there is a limitation of existing resources at the company to improve all these indicators integrally at the same time, the model can provide the priority of environmental indicator which should be considered and improved immediately through a continuous improvement project.

Based on the findings in this research these are recommendations for the company X:

a. Disseminate the approach to environmental evaluation established herein to every division particularly to quality control team in each department. This alleviates the lack of knowledge, skill and experience on the occasions that experts and people dealing with the environmental impacts leave the company or change position within the company.
b. Although the company has implemented wastewater treatment systems to control their wastewater quality, other indicators (namely energy consumption, solid waste and reprocessed material) also proved to be highly influential on the environmental performance to the extent that energy consumption is as significant as wastewater treatment.

c. The company has to target the improvement of environmental indicators to improve quality performance such as cost and quality and environmental impacts.
d. The company should regularly review their KPIs and conduct environmental evaluations to ensure they can continuously control and/or their environmental impact.

The implementation of EPE model is a long term-programme involving the participation of employees from all levels and all functions within an organisations. The big challenge that may occur during the application of the proposed model in real-life situation is the lack of total commitment and support from the top management for development and implementation of an effective EPE. Then the organisation should disseminate their policy of environment to all of their employees. Further actions should be taken such as particular training of the employees related to EPE process including how to determine the environmental indicators and how the process will be conducted; and also adequate resource allocations.

6.6 Concluding remarks

This chapter demonstrated the application of the environmental performance evaluation model using design for six sigma (DFSS), fuzzy expert system and QFD with environmental concerns as a case study at an Indonesian textile industry. This was accomplished by addressing the qualitative evaluation via expert judgment using fuzzy concept and FIS. In the meantime the application also demonstrated that the proposed model is flexible enough to be modified and customised for other similar situations, and can be integrated into continuous improvement methodology to achieve overall competitiveness of product and customer satisfaction. It was also demonstrated that on the occasion of resource limitations, the company can work on less number of top significant factors to improve the negative environmental impacts at less cost.

Chapter Seven

Conclusions and Recommendations for Further Work



7.1 Introduction

This chapter presents the conclusion of this research and goes some way towards answering the research questions posed in Chapter 2 (Section 2.6), followed by recommendations for further work.

7.2 Conclusions

This thesis aimed at developing an environmental performance evaluation model to be integrated into the early stages of the product design and development processes, via DFSS and FIS, for the purpose of achieving continuous positive environmental impacts by industries. This is in contrast to the current approach to environmental performance by industry which is implemented at later stages of production and displays many weaknesses for practicing continuous improvement to the environment.

Although the literature review showed that this evaluation needs to be initiated in the first stages of product design and development there is no guideline on how to determine environmental indicators appropriate for a company's circumstances and its environmental business goal. In addition, this evaluation needs to be initiated within internal aspects of an organisation and link it to external aspects to address external requirements. A review of the available literature suggested a need to introduce environmental indicators as an operational objective and set these indicators as a target for an improvement project.

Most of the existing environmental performance evaluations are not designed to address the above-mentioned deficiencies whereas the use of DFSS and FIS in this research proved to be promising and help fill this gap. The proposed model which employed the integration of DFSS and FIS facilitates the determination of appropriate environmental indicators and metrics that can be evaluated, monitored and integrated into a continuous environmental improvement project.

The research objectives were achieved via the research methodology and tools for modelling of environmental performance evaluation (Chapter 3), approach to modelling of environmental performance evaluation (Chapter 4), modelling of environmental performance evaluation (Chapter 5), and case study (Chapter 6). Based on these steps, the development of an environmental performance evaluation model in this research began

with the quantitative presentation of fuzzy QFD with environmental concerns to determine environmental requirements, environmental indicators and prioritise these indicators based on expert knowledge. The next stage was the application of the integration of FIS and Taguchi method to develop the model. The relationship between input and output variables was established via transfer algorithm. The input variables are environmental indicators and output variables refer to the environmental performance translated into linguistic terms. The fuzzy concept and TFNs were used to represent the range of each membership function. The Taguchi method was conducted to analyse the main contribution of environmental indicators to environmental performance. The effectiveness of the proposed model presented in this thesis was illustrated via a case study where the proposed model is flexible enough to be modified and further developed to meet environmental requirements and a company's environmental goals. Via the case study it was demonstrated that the application of the model is straightforward and produces useful practical results.

It was demonstrated that the fuzzy QFD framework:

- can be used as a tool to deepen the understanding of integrating environmental aspects including environmental requirements and indicators as the first step in product design and development; and
- can determine and prioritise environmental indicators that are expected to greatly influence environmental performance.

Also with the application of FIS and Taguchi method it was shown that:

- FIS can be employed to design an environmental performance evaluation which involves expert judgments and uses linguistic terms;
- transfer algorithm can be used to represent the relationship between input and output variables;
- fuzzy concept with linguistic terms and TFNs can be used to determine the appropriate metric of environmental indicators based on expert's judgment;
- fuzzy concept and TFNs can be used to determine the range of membership function for each indicator; and
- FIS can be used to optimise a transfer algorithm of environmental performance evaluation process.

Via the application it was demonstrated that this research is a significant contribution to the environmental performance evaluation for a manufacturing company by providing a practical quantitative model that will assist the expert team and managers to evaluate, control, monitor and also redesign their environmental performance evaluation process by using the concept of DFSS and FIS, thus helping them meet their strategic environmental business goals.

The major advantage of the proposed environmental performance evaluation model is that it can be applied to any type of organisation or company including small-medium enterprises (SMEs) and can be adopted for different frameworks of environmental indicators (*EPIs, EMIs, and ECIs*) and indicates that this model is flexible and user friendly. Results from this research can enhance the understanding and knowledge in this particular field especially in regards to the environmental performance evaluation process. The benefits can be seen from two points of view (knowledge development and company's use) as follows.

The benefits from the knowledge development point of view are:

- provide a new approach for developing an environmental performance evaluation model;
- provide a manageable and practical way and solution in developing environmental performance evaluations to achieve the company's environmental business goals; and
- provide a framework for the environmental performance evaluation that is flexible enough to be further developed.

The benefits from the company's point of view are:

- propose a better comprehensive framework of environmental performance evaluation in a company based on real and current conditions to achieve their environmental goals; and
- help the company determine appropriate environmental indicators and metrics to design and evaluate environmental performance by prioritising environmental indicators for improvement.

7.3 Recommendations for further work

This research project has achieved significant results in designing an environmental performance evaluation model in a company or industry to establish self-managing teams to enhance environmental performance however there are other aspects to explore such as:

- modifying the proposed model in different structures of environmental indicators;
- integrating the proposed model into continuous improvement methodology like lean six sigma to address the improvement in both quality and environmental performance;
- expanding the model to include more indicators;
- adapting the proposed model to a quality management model that is highlighted as an area for extension which is briefly explained in Section 5.6;
- developing a mathematical sub-model and integrate it into the model to evaluate associated environmental costs caused by the low achievement of environmental indicators; and
- developing the proposed model further through the integration of fuzzy inference system and artificial neural network for environmental performance evaluation.
- Since it is recognised that the human assessment of the QFD approach is always subjective and imprecise, the process to determine the importance weights for the customer requirements is an essential and crucial process. The integration of fuzzy AHP with QFD approach can be employed to determine the importance weights for the customer requirements (Kwong and Bai 2003). Therefore it is recommended the customer requirements be extended as environmental requirements to address environmentally friendly products. Then these requirements be structured into different hierarchy levels to be used for pairwise comparison in AHP approach. The pairwise comparison can be assessed by employing fuzzy representation with triangular fuzzy members.

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Appendix 1: Questionnaires

Questionnaires (semi-structured interviews)

A. **Company background**

Please give any details for the related questions, if available

1. What is the name of your company?
2. When was your company established?
3. How many types and numbers of products are produced?
4. How many employees are working in your company?

B. Production Processes

1. How many types and number of production machines are installed in your company?
2. What is the production capacity?
3. Do you apply some approaches to improve the process and product quality?

C. Current Key performance Indicators (KPIs)

Please give any details for the related questions, if available

1. Can you please explain what are the main KPIs used to measure the quality and environment of your product or process?
2. Are they based on a specific framework and if so how was this determined?
3. How often are the KPI's reviewed?
4. How are new targets and goals made?
5. Do the measures reinforce the firm's strategy?
6. Which ones?
7. Do you concern on environmental requirements to improve your product and processes?
8. How much emphasis is currently placed on measuring environmental requirements related to?
    a. materials
    b. energy consumption
    c. water consumption

d. waste
e. air emission
f. others

9. Do some measures focus on environmental issues?
10. Which ones?

D. **Environmental performance Evaluation**

Please give any details for the related question, if available

1. Have you had any system to evaluate environmental performance?
2. If yes, how was the system carried out?
3. Please give details for environmental evaluation performed.
4. What are the main indicators used to measure environmental evaluation?
5. Are they based on a specific framework and if so how was this determined?
6. How much emphasis is currently placed on measuring environmental indicators related to?
   a. materials
   b. energy consumption
   c. water consumption
   d. waste
   e. air emission
   f. wastewater
   g. others
   h. How often the environmental indicators reviewed?
   i. How are new targets and goals made?
   j. Are you aware of the environmental indicators in the environmental performance evaluation?
   k. Do the measures of environmental indicators reinforce company's environmental strategy?
   l. Which ones?
   m. Do some measures focus on environmental satisfaction?
   n. Which ones?
   o. Do you think that the environmental performance evaluation brought potential benefits to your company? In which aspects?

Appendix 2: Calculation the weight of environmental requirements in QFD from expert's opinion

Environmental requirements		Expert 1 **(a)**			Expert 2 **(b)**			Expert 3 **(c)**			Fuzzy average (Equation 5.1) **(d)**			Defuzzification (Equation5.2)
		a	*b*	*c*	*a*	*B*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	**(e)**
ER_1	Waste reduction	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33	7.58
ER_2	Pollution impact reduction	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00	7.00
ER_3	Less material usage	4	5	6	8	9	9	6	7	8	6.00	7.00	7.67	6.92
ER_4	Less energy usage	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67	8.17
ER_5	Less water usage	4	5	6	4	5	6	4	5	6	4.00	5.00	6.00	5.00
ER_6	Easy to process	4	5	6	6	7	8	4	5	6	4.67	5.67	6.67	5.67
ER_7	Safer to landfill	4	5	6	6	7	8	6	7	8	5.33	6.33	7.33	6.33
ER_8	Safer emission	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33	6.33
ER_9	Less harmful to the living environment	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33	6.33
ER_{10}	Disposable	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33	6.33

Appendix 3: Calculation the relationship matrix between environmental requirements and environmental indicators in QFD from expert's opinion

Environmental requirements		EI_1 : Materials											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_2	Pollution impact reduction	0	0	0	0	0	0	0	0	0	-	-	-
ER_3	Less material usage	8	9	9	6	7	8	8	9	9	7.33	8.33	8.67
ER_4	Less energy usage	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	easy to process	6	7	8	8	9	9	6	7	8	6.67	7.67	8.33
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	0	0	0	0	0	0	0	0	0	-	-	-
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Environmental requirements		EI_2 : Toxic materials											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*z*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	0	0	0	0	0	0	0	0	0	-	-	-
ER_2	Pollution impact reduction	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33
ER_{10}	Disposable	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33

Environmental requirements		EI_3 : Reprocessed materials											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	8	9	9	6	7	8	8	9	9	7.33	8.33	8.67
ER_2	Pollution impact reduction	0	0	0	0	0	0	0	0	0	-	-	-
ER_3	Less material usage	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33
ER_4	Less energy usage	6	7	8	8	9	9	8	9	9	7.33	8.33	8.67
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	4	5	6	6	7	8	6	7	8	5.33	6.33	7.33
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Environmental requirements		EI_4: Energy consumption											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	8	9	9	6	7	8	6.67	7.67	8.33
ER_2	Pollution impact reduction	8	9	9	6	7	8	8	9	9	7.33	8.33	8.67
ER_3	Less material usage	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33
ER_4	Less energy usage	8	9	9	8	9	9	8	9	9	8.00	9.00	9.00
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67
ER_9	Less harmful to the living environment	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Environmental requirements		EI_5 : Water consumption											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_2	Pollution impact reduction	4	5	6	4	5	6	6	7	8	4.67	5.67	6.67
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	4	5	6	4	5	6	6	7	8	4.67	5.67	6.67
ER_{10}	Disposable	6	7	8	4	5	6	4	5	6	4.67	5.67	6.67

Environmental requirements		EI_6 : Air emission											
		expert 1			expert 2			expert 3			average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	4	5	6	6	7	8	4	5	6	4.67	5.67	6.67
ER_2	Pollution impact reduction	6	7	8	4	5	6	4	5	6	4.67	5.67	6.67
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33
ER_9	Less harmful to the living environment	4	5	6	4	5	6	6	7	8	4.67	5.67	6.67
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Environmental requirements		EI_7 : Noise/vibration											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	4	5	6	4	5	6	6	7	8	4.67	5.67	6.67
ER_2	Pollution impact reduction	6	7	8	4	5	6	4	5	6	4.67	5.67	6.67
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	4	5	6	6	7	8	4	5	6	4.67	5.67	6.67
ER_{10}	Disposable	0	0	0	0	0	0	0	0	0	-	-	-

Environmental requirements		EI_8 : Water pollution											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	4	5	6	6	7	8	6	7	8	5.33	6.33	7.33
ER_2	Pollution impact reduction	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	0	0	0	0	0	0	0	0	0	-	-	-
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33
ER_{10}	Disposable	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33

Environmental requirements		EI_9 : Solid waste											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	8	9	9	8	9	9	7.33	8.33	8.67
ER_2	Pollution impact reduction	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33
ER_3	Less material usage	6	7	8	6	7	8	6	7	8	6.00	7.00	8.00
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	6	7	8	6	7	8	8	9	9	6.67	7.67	8.33
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_{10}	Disposable	6	7	8	4	5	6	6	7	8	5.33	6.33	7.33

Environmental requirements		EI_{10} : Wastewater treatment											
		expert 1			expert 2			expert 3			Average		
		x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
ER_1	Waste reduction	6	7	8	8	9	9	6	7	8	6.67	7.67	8.33
ER_2	Pollution impact reduction	8	9	9	8	9	9	6	7	8	7.33	8.33	8.67
ER_3	Less material usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_4	Less energy usage	0	0	0	0	0	0	0	0	0	-	-	-
ER_5	Less water usage	6	7	8	8	9	9	8	9	9	7.33	8.33	8.67
ER_6	Easy to process	0	0	0	0	0	0	0	0	0	-	-	-
ER_7	Safer to landfill	4	5	6	6	7	8	4	5	6	4.67	5.67	6.67
ER_8	Safer emission	0	0	0	0	0	0	0	0	0	-	-	-
ER_9	Less harmful to the living environment	6	7	8	6	7	8	4	5	6	5.33	6.33	7.33
ER_{10}	Disposable	8	9	9	6	7	8	6	7	8	6.67	7.67	8.33

Appendix 4: Calculation the value of environmental indicators in QFD from expert's opinion

Environmental requirements		The value of environmental indicators (EI_1 : Materials)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	5.33	6.33	7.33	40.44	48.03	55.61	48.03
ER_2	Pollution impact reduction	7.00	-	-	-	-	-	-	-
ER_3	Less material usage	6.92	7.33	8.33	8.67	50.72	57.64	59.94	56.49
ER_4	Less energy usage	8.17	6.00	7.00	8.00	49.00	57.17	65.33	57.17
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	6.67	7.67	8.33	37.78	43.44	47.22	42.97
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	-	-	-	-	-	-	-
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Environmental requirements		The value of environmental indicators (EI_2 : Toxic materials)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	-	-	-	-	-	-	-
ER_2	Pollution impact reduction	7.00	7.33	8.33	8.67	51.33	58.33	60.67	57.17
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	6.67	7.67	8.33	42.22	48.56	52.78	48.03
ER_{10}	Disposable	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11

Environmental requirements		The value of environmental indicators (EI_3 : Reprocessed materials)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	7.33	8.33	8.67	55.61	63.19	65.72	61.93
ER_2	Pollution impact reduction	7.00	-	-	-	-	-	-	-
ER_3	Less material usage	6.92	6.67	7.67	8.33	46.11	53.03	57.64	52.45
ER_4	Less energy usage	8.17	7.33	8.33	8.67	59.89	68.06	70.78	66.69
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	5.33	6.33	7.33	30.22	35.89	41.56	35.89
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Environmental requirements		The value of environmental indicators (EI_4 : Energy consumption)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	6.67	7.67	8.33	50.56	58.14	63.19	57.51
ER_2	Pollution impact reduction	7.00	7.33	8.33	8.67	51.33	58.33	60.67	57.17
ER_3	Less material usage	6.92	5.33	6.33	7.33	36.89	43.81	50.72	43.81
ER_4	Less energy usage	8.17	8.00	9.00	9.00	65.33	73.50	73.50	71.46
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	5.33	6.33	7.33	30.22	35.89	41.56	35.89
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	7.33	8.33	8.67	46.44	52.78	54.89	51.72
ER_9	Less harmful to the living environment	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Environmental requirements		The value of environmental indicators (EI_5 : Water consumption)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	5.33	6.33	7.33	40.44	48.03	55.61	48.03
ER_2	Pollution impact reduction	7.00	4.67	5.67	6.67	32.67	39.67	46.67	39.67
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	7.33	8.33	8.67	36.67	41.67	43.33	40.83
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	4.67	5.67	6.67	29.56	35.89	42.22	35.89
ER_{10}	Disposable	6.33	4.67	5.67	6.67	29.56	35.89	42.22	35.89

Environmental requirements		The value of environmental indicators (EI_6 : Air emission)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	4.67	5.67	6.67	35.39	42.97	50.56	42.97
ER_2	Pollution impact reduction	7.00	4.67	5.67	6.67	32.67	39.67	46.67	39.67
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	5.33	6.33	7.33	43.56	51.72	59.89	51.72
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	6.67	7.67	8.33	42.22	48.56	52.78	48.03
ER_9	Less harmful to the living environment	6.33	4.67	5.67	6.67	29.56	35.89	42.22	35.89
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Environmental requirements		The value of environmental indicators (EI_7 : Noise/vibration)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	4.67	5.67	6.67	35.39	42.97	50.56	42.97
ER_2	Pollution impact reduction	7.00	4.67	5.67	6.67	32.67	39.67	46.67	39.67
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	4.67	5.67	6.67	29.56	35.89	42.22	35.89
ER_{10}	Disposable	6.33	-	-	-	-	-	-	-

Environmental requirements		The value of environmental indicators (EI_8: Water pollution)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	5.33	6.33	7.33	40.44	48.03	55.61	48.03
ER_2	Pollution impact reduction	7.00	6.00	7.00	8.00	42.00	49.00	56.00	49.00
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	5.33	6.33	7.33	26.67	31.67	36.67	31.67
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	-	-	-	-	-	-	-
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11
ER_{10}	Disposable	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11

Environmental requirements		The value of environmental indicators (EI_9 : Solid waste)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	7.33	8.33	8.67	55.61	63.19	65.72	61.93
ER_2	Pollution impact reduction	7.00	5.33	6.33	7.33	37.33	44.33	51.33	44.33
ER_3	Less material usage	6.92	6.00	7.00	8.00	41.50	48.42	55.33	48.42
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	-	-	-	-	-	-	-
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	6.67	7.67	8.33	42.22	48.56	52.78	48.03
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11
ER_{10}	Disposable	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11

Environmental requirements		The value of environmental indicators (EI_{10} : Wastewater treatment)							
		w	r			Elements of A_1			Defuzzification
			x	y	z	x	y	z	
ER_1	Waste reduction	7.58	6.67	7.67	8.33	50.56	58.14	63.19	57.51
ER_2	Pollution impact reduction	7.00	7.33	8.33	8.67	51.33	58.33	60.67	57.17
ER_3	Less material usage	6.92	-	-	-	-	-	-	-
ER_4	Less energy usage	8.17	-	-	-	-	-	-	-
ER_5	Less water usage	5.00	7.33	8.33	8.67	36.67	41.67	43.33	40.83
ER_6	Easy to process	5.67	-	-	-	-	-	-	-
ER_7	Safer to landfill	6.33	4.67	5.67	6.67	29.56	35.89	42.22	35.89
ER_8	Safer emission	6.33	-	-	-	-	-	-	-
ER_9	Less harmful to the living environment	6.33	5.33	6.33	7.33	33.78	40.11	46.44	40.11
ER_{10}	Disposable	6.33	6.67	7.67	8.33	42.22	48.56	52.78	48.03