INVESTIGATION ON IMPROVING SUSTAINABILITY AND CUSTOMER SATISFACTION IN NEW PRODUCT DEVELOPMENT USING MULTI CRITERIA DECISION SUPPORT TOOLS

A THESIS

Submitted by

BIJU P.L.

in fulfillment for the award of the degree

of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MECHANICAL ENGINEERING

GOVERNMENT ENGINEERING COLLEGE - THRISSUR

UNIVERSITY OF CALICUT

CALICUT

December 2015

UNIVERSITY OF CALICUT

BONAFIDE CERTIFICATE

Certified that this thesis titled **“INVESTIGATIONS ON IMPROVING SUSTAINABILITY AND CUSTOMER SATISFACTION IN NEW PRODUCT DEVELOPMENT USING MULTI CRITERIA DECISION SUPPORT TOOLS”** is the bonafide work of Mr. BIJU P.L. who carried out the research under my supervision. Certified further that to the best of my knowledge the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion of this or any other candidate.

Dr. P.R. SHALIJ
(SUPERVISOR)
Associate Professor
Department of Production Engineering
Govt. Engineering College, Thrissur.

Place:
Date:

ABSTRACT

The recent change in the preferences of customers from quality and cost to sustainable products reflects their concern for a clean and green planet. Manufacturing organizations are striving to incorporate sustainability requirements in their products not only to improve brand value but also as the commitment towards the future generation. Inclusion of sustainability aspects in the very beginning of product development has thus emerged as an integral part of design process in recent years. Manufacturers are now keen on fulfilling this requirement by utilizing innovative tools and techniques in product development that help them to design sustainable products.

Several tools and techniques have been developed by researchers for sustainable new product development. Many of these tools and techniques in sustainable product development consider sustainability requirements as part of customer requirements. This may reduce the importance of sustainability requirements compared to the customer requirements. In addition, the tools that reckon customer requirements and sustainability requirements separately, do not weigh them based on their importance. These tools do not ponder all the three dimensions of sustainable development namely environmental, social and economic. These situations have urged researchers to develop tools that satisfy sustainability requirements in the early stages of product development.

Design and development of a product development tool that incorporates sustainability requirements in the early stages of product development is the primary aim of this thesis work. A new tool named ‘Customer and Sustainability Requirement Evaluation Matrix’ (CSRE Matrix) has been developed as part of this research work. CSRE Matrix is a

qualitative tool that helps the designers to identify best option at each stage of product development cycle. For each the stage of product development cycle, a CSRE Matrix is constructed. Each option is termed as a path and for each option, path scores are calculated based on the level of fulfillment of customer and sustainability requirements. Various combinations of paths and their total path scores are calculated subsequently. The combination of paths with the highest total path score is selected as the best combination path for the development of a customer satisfying sustainable product.

In CSRE Matrix, weighing of customer requirements and sustainability requirements are carried out using three different decision making methods namely, Rank Order Centroid (ROC) Weight method, Analytic Hierarchy Process (AHP) method and Fuzzy Analytic Hierarchy Process (FAHP) method. Based on the nature of the product and availability of data, designers can select an appropriate method among these three decision making methods.

After designing CSRE Matrix, case studies were conducted in two typical Indian manufacturing companies for illustrating the effectiveness of the CSRE Matrix. The first case study was carried out in Duropack industries, Mundur, Kerala. In this case study, a sustainable product development path that satisfies various customer requirements and sustainability requirements was evolved for a product – 500 ml edible oil container bottle. The validation of the proposed tool was also carried out. A design team was constituted in the company to weigh various ‘Customer Requirements’ and ‘Sustainability Requirements’. Rank Order Centroid (ROC) weight method was used for weighing ‘Customer Requirements’ and ‘Sustainability Requirement’. In the same company, CSRE Matrix using Analytic Hierarchy Process (AHP)’ was also tested. Here, CSRE Matrix was applied for developing a sustainable new product namely 750 ml container bottle for ayurvedic medicine.

The third case study was conducted in John’s umbrella manufacturing company, located in Alappuzha, Kerala. In this case study, Fuzzy Analytic Hierarchy Process (FAHP) method was used in CSRE Matrix for weighing various customer requirements and sustainability requirements. Sustainable product development options under different stages of product development cycle for a product named walking stick umbrella was evolved in this case study. The validation of the tool in the industry was also carried out to find the acceptability and effectiveness of the CSRE Matrix.

The case studies conducted and the subsequent feedback from the practitioners have established the usefulness of the CSRE Matrix as a tool for the new sustainable product development. All the three case studies have resulted in identifying the options of product development stages that produce customer satisfying sustainable products. The feedback obtained by the practitioners also confirms the applicability of CSRE matrix in industries for new sustainable product development.

Further to the construction of CSRE Matrix, a decision support system for the easy implementation of CSRE Matrix named ‘CSREMDSS’ (Decision Support System of CSRE Matrix) was also developed. It helps the designers in new product development, where customer requirements and sustainability requirements are weighed separately using either ROC weight method or AHP method. Various CSRE Matrices were developed by the decision support system according to the inputs fed by the designers. Decision support system of CSRE Matrix finally arrives at the best combination path with best options from each product development stage for the development of a customer satisfying sustainable product.

The research work is concluded with anticipation that CSRE Matrix will help the practicing engineers particularly in the product design to develop new products with a sustainable perspective. The decision support system ‘CSREMDSS’ shall be beneficial for them to do the computational works associated with the CSRE Matrix and also to carry out the compatibility check in between the selected components. Even though CSRE Matrix’s potential has proved in industries, application in various industries and process plants may increase its acceptability as a tool for new product development globally. Moreover, instead of a qualitative approach, applying a quantitative approach by incorporating various indicators of sustainability requirements and customer requirements in CSRE Matrix shall further increase its credibility.

ACKNOWLEDGEMENT

I bow my head before the Almighty Lord whose grace was with me always throughout the research work.

Creative guidance makes a scientific research qualitative and this has been imparted to me by Dr. Shalij P.R, Associate Professor, Department of Production Engineering, Govt. Engineering College, Thrissur, as a helpful guide. I wish to express my sincere and heartfelt gratitude to him for his guidance, inspiration and support which made this work possible. I sincerely thank the Doctoral Committee members, Dr. K.R Jayadevan, Dr. Latha Raj and Dr. Haris Naduthodi, for providing valuable comments and suggestions during this research works.

I extend my whole hearted thanks to Dr. Vijayakumar, the joint director of Kerala Technical University (The Principal of GEC, Thrissur, during the period 2008-2014) for his healthy co-operation and encouragement. I am also thankful to Dr. Indiradevi K.P, Principal, Government Engineering College, Thrissur and Prof. C.P Sunilkumar, Head of the Mechanical Engineering Department, Government Engineering College, Thrissur, for providing the facilities to successfully carry out this research works.

I express my sincere gratitude to Prof M. Parameswaran, Former Head, Production Engineering, Prof Jayasree N., Head, Production Engineering, faculty and supporting staff members of Production Engineering for giving an opportunity to carry out my research work in the Department of Production Engineering, Government Engineering College Trichur.

I extent my sincere thanks to Dr. K. E George (The Principal, AISAT, Kalamassery), Dr. E.A Jasmine (Professor, Electrical department, GEC, Thrissur) and Mr. Biju C. Devassy (Design Consultant, TCS, Cochin) whose technical help have been a source of inspiration. I also thank the management of M/s. Duropack Industries, Mundur and M/s. John’s Umbrella, Alappuzha for allowing me to carry out the implementation studies.

I would like to place on record my gratitude to Centre for Research and Development (CERD) - Government of Kerala, for selecting me for the research scholarship.

My gratitude goes to my mother, wife and offspring for their understanding and unconditional support throughout this research works. My gratitude also goes to my sister Sr. Jaya Jees F.C.C and to my late father P.L Louis who were the inspiration in all my studies.

Thrissur - 9 BIJU P.L
21-12-2015

TABLE OF CONTENTS

CHAPTER NO: TITLE PAGE NO.

CHAPTER NO: TITLE PAGE NO.

CHAPTER NO: TITLE PAGE NO.

CHAPTER NO: TITLE PAGE NO.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND NOTATIONS

AHP	Analytic Hierarchy Process
BPW	Business Policy Weight
CR	Customer Requirements
C_R	Consistency Ratio
C_I	Consistency Index
CSRE	Customer and Sustainability Requirements Evaluation
DiS	Disposal Selection
DrS	Distribution Selection
DS	Design Selection
DSS	Decision Support Systems
EB	Excellent Barrier
ED	Easily Degradable
EBP	Economic Bag Packing
EFP	Eco Friendly Packing
ESF	Excellent Surface Finish
EIM	Eco Impact Matrix
FAHP	Fuzzy Analytic Hierarchy Process
HDPE	High Density Poly Ethylene
LBU	Less Breakdown to Ultraviolet
LCA	Life Cycle Assessment
MA	Morphological Analysis
MCA	Minimum Content of Additives
MECO	Material, Energy, Chemicals and Others
MD	More Durable
MDC	Minimum Distribution Cost
MET	Material Energy and Toxicity
MHD	More Heat Dissipation
MMC	Minimum Material Cost
MPC	Minimum Production Cost
MPAC	Minimum Packing Cost
MPS	Manufacturing Process Selection

MPW	Minimum Production Waste
MR	More Recyclable
MS	Material Selection
NPD	New Product Development
PET	Poly Ethylene Terraphthalate
QFD	Quality Function Deployment
RC	Recyclability
ROC	Rank Order Centroid
RW	Reduced Wastage
SD	Sustainable Development
SM	Sustainable Manufacturing
SLCA	Simplified Life Cycle Assessment
SPD	Sustainable Product Development
SSP	Standard Special Packing
US	Usage Selection
UWT	Uniform Wall Thickness
CR_i	Customer requirement, where i = 1 to n
SR_j	Sustainability requirement, where j = 1 to m
CRW_i	Customer requirement weight, where i = 1 to n
SRW_j	Sustainability requirement weight, where j = 1 to m
$R_k a_i$	Rating of option k against i^{th} customer requirement, where k = 1 to z; i = 1 to n
$R_k b_j$	Rating of option k against j^{th} sustainability requirement, where k = 1 to z; j = 1 to m
$CRS_k a_i$	Customer requirement score of option k, against i^{th} customer requirement, where k = 1 to z & i = 1 to n
$SRS_k b_j$	Sustainability requirement score of option k, against j^{th} sustainability requirement, where k = 1 to z & j = 1 to m
$TCRS_k$	Total customer requirement score of option k, where, k = 1 to z
$TSRS_k$	Total sustainability requirement score of option k, where, k = 1 to z
$CSRE_k$	Customer and sustainability requirement evaluation score of option k, where, k = 1 to z
O^{1}_{gi}	A triangular fuzzy number that can be represented by (a_{ij}, b_{ij}, c_{ij}), where i = 1 to n & j = 1 to m

CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

The processes and methods of nature were always sustainable ever since the beginning of life on the planet Earth. Modern production and consumption practices have raised several issues on the environmental degradation and the very existence of the mankind (Jones et al., 2011). However, most of the inventions of mankind had little thought on the sustainability of nature. Protection of the environment was not a concern till the second half of 20th century (Meadows et al., 1972). Increased pace of industrialization and changing requirements of customers have supplemented the induction of non-sustainable products and production processes (Jovane et al., 2008). By the time mankind realized the importance of sustainable product design and production practices, irrecoverable damages have already been occurred to the planet.

Traditional methods of product design have focused more on reduction of costs, improvement of quality and reduction of time to market and thus satisfying the needs of the customers (Garbie, 2013). Later periods of 20th century and beginning of the 21stcentury observed a paradigm shift from this approach. The new approach focused on the design of eco-friendly and sustainable products, where environment friendly production practices are considered either equal to or more important than the cost, quality and time to market. However, this paradigm shift is unlikely to happen in practice as the companies are focusing primarily on making profits for their existence (Kaebernick et al., 2003).

Rio De Janeiro conference of United Nations (UN Conference on Environment and Development in Rio De Janeiro-1992) reiterated that the unsustainable production and consumption patterns are detrimental to the sustainable development of the world (Liu et al., 2010). Regulatory bodies have started pursuing regulatory measures on environmental protection for the adoption of sustainable production practices in the organizations worldwide (Greenberg and Quillian, 2012). Customers have also started evaluating environmental impact of the products prior taking a decision on procurement (Abdalla et al., 2012). Nevertheless, implementation of sustainable production practices has not got momentum to a significant level in industries (Hutchins et al., 2013).

The importance of sustainability in the design and manufacturing of products is not recognized by organizations, particularly by Micro, Small and Medium enterprises (Burke and Gaughran, 2007). In the present day business environment, MSMEs are the major players of economic activities particularly in the developing countries. The role of MSMEs is recognized as critical to local social and economic development of countries (Rayman-Bacchus and He 2014). They are finding difficulties in raising fund for sustainable initiatives (O’Brien, 2002).

The collective impact of MSMEs on economy, environment and society is one of the main barriers towards achieving sustainable development (Burke and Gaughran, 2007). Business world has reached to a situation where only sustainable products would be survived in the long run due to the climbing cost of natural resources, government’s mandates and regulations (Ziout et al., 2013). In this context, manufacturers shall be aware of the sustainable practices in design and processing of products. The designers and process engineers need to be equipped with tools that help to analyze sustainability of design and process to bring out a customer satisfying sustainable product. This thesis reports the work carried out towards developing a tool for the design and development of customer satisfying sustainable products.

1.2 PROBLEM DEFINITION

Most of the production processes of goods and services are unsustainable and the reasons for today's environmental problems (Koltun, 2010). Manufacturers should strive for a paradigm shift from their cost effective non-sustainable production, consumption and disposal practices to sustainable manufacturing practices. Interventions of law making authorities are essential to frame strategies on technological development and consumer policies for reducing the adverse environmental impact of the production and consumption practices (Liu et al., 2010). Even though various regulations have been introduced for accomplishing environmentally conscious manufacturing practices, the implementations of these regulations still lack momentum (Umeda et al., 2012). This is due to the fact that many of these manufacturing organizations lack awareness on sustainability and the legislations on sustainability (Burke and Gaughran, 2007).

The existing product development techniques rely on the traditional cost/profit models to achieve high quality and high profit at reduced cost (Vinod and Rathod, 2010). However, during last two decades, efforts have been taken to incorporate environmental consideration also into product development. The integration of environmental considerations in product development has been dealt by researchers using different strategies.

Introduction of environmental considerations at the early stages of the product development is extremely important for reducing the environmental impacts of products

(Charter and Belmane, 1999). For the development of a sustainable product, the three dimensions of sustainability namely environment, social and economic impacts of the product need to be reckoned carefully (Elkington, 1998). Instead of considering three dimensions of sustainability, many of the recent research works focus on one or two dimensions of sustainability (Ghadimi et al., 2012; Yan et al., 2009). In addition, most of the current product development practices ponder sustainability requirements as part of customer requirements.

Assessing sustainability requirements along with customer requirements, causes sustainability requirements get weighed very low and their importance in the design gets reduced (Kaebernick et al., 2003). Also, all stages of product development cycle need to be assessed for sustainability (Ramani et al., 2010). In addition, implementation of an organization policy on level of fulfillment of sustainability and customer requirements is also required in sustainable new product development (Biju P.L et al., 2015).

Sustainable product development tools have to assess all the three dimensions of sustainability and weigh the elements of sustainability and its sub-elements (Ghadimi et al., 2012). A new product development (NPD) tool that support all the requirements discussed earlier will be helpful for the designers and practicing engineers in designing sustainable products by satisfying customer requirements. A product development tool that carefully carries out trade-offs between the three dimensions of sustainable development and customer requirements separately is currently not available for the product designers.

1.3 OBJECTIVES

The necessity of developing a new product development tool that helps in designing and producing a customer satisfying sustainable product was recognized as the problem of research. This problem is taken up for the doctoral work and the following objectives were identified.

- To device a method that incorporate Sustainability Requirements (SRs) and Customer Requirements (CRs) into new product development.
- To develop a tool that weighs SRs and CRs separately and evaluate different options in each stage of product development cycle based on the fulfillment level of CRs and SRs.
- To carry out implementation studies in different industries to validate the usefulness of the proposed tool.
- To design and develop a decision support system to facilitate easy use of the proposed tool by the practitioners.

1.4 RESEARCH METHODOLOGY

The methodology adopted for pursuing the research work is shown in Fig. 1.1. Since the research area was Sustainable Manufacturing, the literature review on sustainable manufacturing and sustainable product development was carried out. Databases such as Science Direct, Taylor and Francis, EmeraldInsight, Inderscience, Springerlink were searched for collecting peer reviewed papers in the domain of sustainable manufacturing and sustainable product development. The focus of the survey was new product development tools, sustainability assessment of products and sustainable new product development tools.

Further, the search was focused on sustainable product development tools. Research papers pertaining to sustainable product development tools that describe sustainability and environment assessment were collected for an elaborate study. Review of tools and techniques for sustainable product development paved way to the design of a new tool named 'CSRE Matrix' for customer satisfying sustainable product development. The proposed tool required a decision support system for the easy implementation for the practitioners and it was developed. Implementation studies were conducted for the development of three different products in industries. The feedback of expert's on 'CSRE Matrix' was collected and statistically tested for the acceptance of the tool.

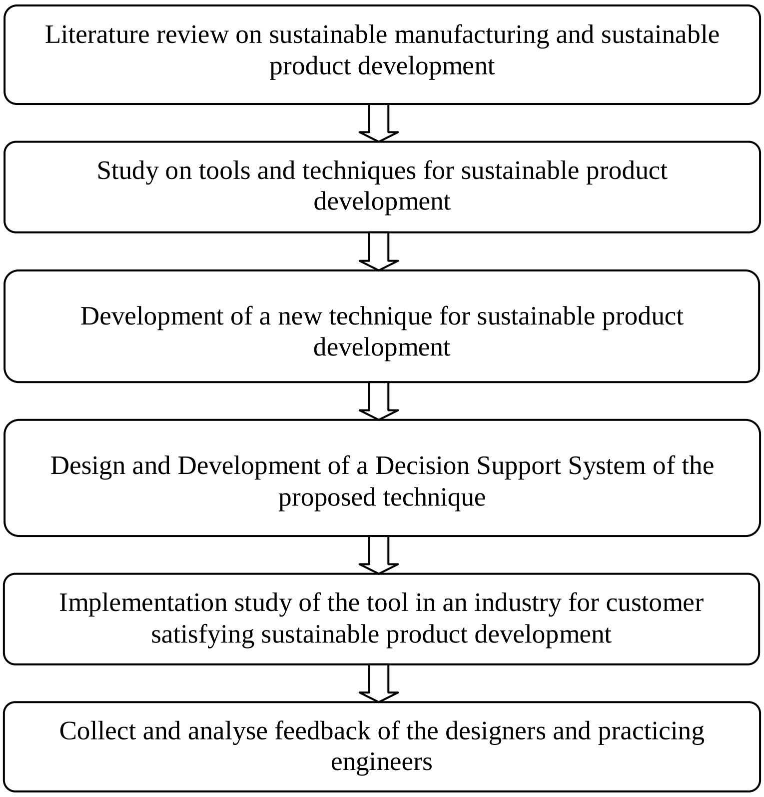


Figure 1.1 Research methodology

1.5 CHAPTER SCHEMATA

The thesis report is organized in 9 chapters. The pictorial representation of the organization of the chapters is shown in Fig. 1.2. Chapter - 1 discusses about the importance of sustainable development and sustainable product development. Limitations of the current sustainable product development tools, problems identified, objectives of research and the methodology adopted for research are also discussed in this chapter.

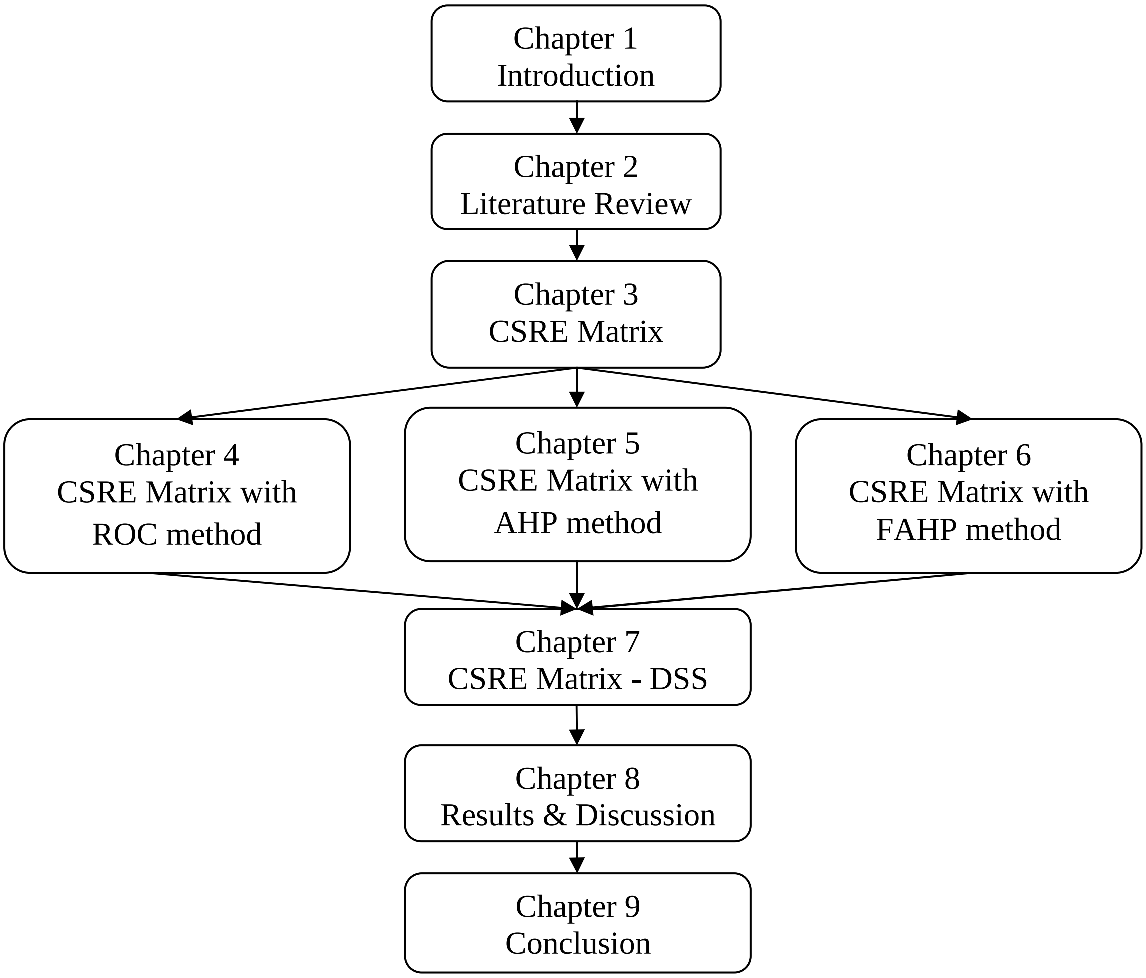


Figure 1.2 Schemata of Chapters

The method adopted to conduct literature review and the major outcomes are presented in Chapter 2. Various terms connected with sustainability, different tools, techniques and methods used to assess or design environmental/sustainability aspects of products were elucidated. Taxonomy of 29 selected tools based on their application was carried out subsequently. This taxonomy helps the designers to select the best tool which is suitable for their organization from a list of 29 tools.

In chapter 3, the design of sustainable product development tool – 'Customer and Sustainability Requirement Evaluation Matrix (CSRE Matrix)' is described. Subsequently, in chapter 4, CSRE Matrix with Rank Order Centroid weight method is explained along with the implementation study conducted in an industry. In chapter 5, CSRE Matrix with Analytic Hierarchy Process (AHP) is described. Implementation study of the tool in industry is also explained in the same chapter.

In chapter 6, explanations of Fuzzy Analytic Hierarchy Approach (FAHP) and its usage in CSRE Matrix are demonstrated. The report of the implementation study carried out in an umbrella manufacturing company is also explained in chapter 6. The development of a decision support system that helps designers and practicing engineers to construct CSRE Matrix is described in chapter 7. In chapter 8, the research results and discussions are included. Eventually in chapter 9, conclusions, limitations and future scope of the thesis are presented.

Efforts have been taken to organize the thesis for a convenient reading and understanding of the research findings and also for its further usage among researchers and practitioners. It is quite natural that designers shall have to go through the entire chapters diligently where as the practitioners obviously skip the chapters which are non beneficial to them. However, an additional idea behind this reporting is to ensure easy and effortless reading and understanding of the report especially without boredom till the end.

1.6 CHAPTER SUMMARY

A number of tools and techniques have been developed for the assessment of environmental performance of the products. These tools can also be used as a supporting tool for new product development where designers can take decision on an alternative process, materials or design by comparing their environmental performances. The search for a new product development tool with a perspective on sustainability led to the need for a sustainable and customer oriented product development tool that satisfy both the customer requirements and sustainability requirements in totality. This was recognized as the problem of research. Hence, this research work is taken up and the objectives were drawn.

CHAPTER 2

LITERATURE REVIEW

2.1 PREAMBLE

'Sustainable Development' and 'Sustainable Manufacturing' are the two catch words of environmental protection initiatives in the recent times. Many global issues such as Global Warming, Acid Rain, Ozone Depletion, Pollution of Air and Water, local issues such as Unemployment, Diseases caused by Chemicals locally and Sound Pollution are the results of non-sustainable practices (Khakee, 1999). Introduction of non-sustainable products and production practices are the primary reason for today's environmental problems (Koltun, 2010; Veleva and E llenbecker, 2001).

Researches on sustainability have been focusing on developing 'Environmentally Conscious Manufacturing Practices' in the last two decade of twentieth century (Despeisse et al., 2012). In the beginning of twenty first century, the focus was on 'Sustainable Manufacturing Practices' that include 'Social' and 'Economic' aspects other than 'Environmental' aspects (Millar and Russel, 2011). Satisfaction of sustainability aspects in manufacturing is a cumbersome task as it has to satisfy the three somewhat mutually contradicting aspects of sustainable development namely environmental, social and economic factors (Byggeth et al., 2007).

The importance of manufacturing sustainable products along with satisfying the needs of the customers gained attention during the later decades of the twentieth century

(Kaebernick et al., 2003). Researches in product development methods were focused on developing tools and techniques that incorporate customer requirements into the products. Numerous methods and approaches such as Quality Function Deployment, Design for Manufacturing, Computer Aided Manufacturing and Concurrent Engineering have been developed for the integration of different stages of the product development and to satisfy customer requirements (Besterfield et al., 2004).

The focus of the current researches on product sustainability is on the development of products and processes that meet sustainability requirements along with customer requirements. This chapter depicts the development of sustainability as a requirement for the sustenance of humanity and the adoption of sustainability principles in the design and manufacturing of products.

The literature available on sustainability aspects and sustainable product development is presented in this chapter. The search for published journal papers was carried out in Emerald insight, Science Direct, Taylor and Francis, inderscience and Springerlink database. Initially a study on the evolution of sustainability as a principle and the sustainable development was carried out which is presented in section 2.2. Then a detailed study of the tools and techniques used for sustainability analysis was carried out. The outcome of this study is presented in section 2.3. The tools and techniques are further classified under three dimensions of sustainability namely - environmental, society and economical dimensions. These classifications are presented in section 2.4.

2.2 EVOLUTION OF ‘SUSTAINABILITY’ AND ‘SUSTAINABLE DEVELOPMENT’

The word ‘sustainability’ has the meaning ‘the capacity to maintain’, ‘the capacity to endure and adapt’ and ‘capability of being sustained’ that link to capacity of durability, stability or even eternalness (Gomes et al., 2014, Starik and Kanashiro, 2013, García-Serna et al., 2007). The word was first introduced by a German miner, Hans Carl von Carlowitz in “*Sylvicultura oeconomica*” in 1973, while referring to sustainable forestry (García-Serna et al., 2007).

The ‘Club of Rome’ formed in the year 1968 as an informal group of independent professionals from politics, industry, science and civil society, gathered for discussing the future of humanity and the planet, highlighted the need for sustainable development in their famous report the ‘limits to growth’ (Meadows et al., 1972). The Brundtland committee constituted by Javier Perez de Cuellar, the then secretary general of United Nations and chaired by Gro Harlem Brundtland, the former prime minister of Norway for the purpose of developing a universal approach to pursue sustainable development in their report ‘Our common Future’ in the year 1987, reinforced this need and grounded worldwide discussions on the term ‘Sustainable Development’ (Brundtland, 1987).

According to Veleva and Ellenbecker, (2001), the word ‘sustainability’ is a vague concept and difficult to define. Sustainability is a ‘fuzzy’ concept having different meanings at different levels of application in different contexts (Weaver et al., 2008). Burke and Gaughran, (2007) also have opined that, the term ‘sustainability’ does not have any international definition.

If sustainability is difficult to define, it will be more difficult to define ‘sustainable development’ and to obtain a unanimous acceptance. Sustainable development as a concept was launched by World Commission on Environment and Development in the year 1987 (Brundtland, 1987) as a global objective, to direct policies getting oriented towards economic, social and ecological systems (Seghezzo, 2009). However, according to Koltun (2010) there are still confusion and conflict about the exact meaning of sustainable development.

The Brundtland committee has defined sustainable development as ‘the development which meets the needs of the present without compromising on the ability of future generations to meet their own needs’ which is considered as the most suitable and widely accepted definition for sustainable development (Tahir and Darton, 2010).

Sustainable development is articulated as people, planet and profit (PPP or P3); where people represent society, planet represents environment and profit represents economy (Heijungs et al., 2010). Accordingly, it has been modeled under three pillars of sustainable development as shown in Fig.2.1. Figure indicates that all the three pillars are equally important to sustain the building of sustainability.

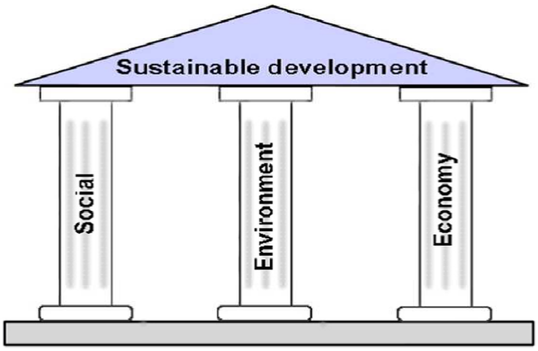


Figure 2.1 The three pillars of Sustainable Development (Heijungs et al., 2010).

Application of sustainable development in products and production processes leads to another concept namely, sustainable manufacturing. Concerns such as global warming and environmental issues have increased the importance of sustainable manufacturing in the recent times (Hu and Bidanda, 2009).

2.2.1 Evolution of Sustainable Manufacturing

As in the case of sustainable development, the term ‘sustainable manufacturing’ also doesn’t have any universal definition (Millar and Russel, 2011). However, a more accepted definition for sustainable manufacturing proposed by the U.S Department of Commerce is ‘the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound’ (Jayal et al., 2010).

Sustainable manufacturing is considered as one of the key challenges of the next decade (Aurich et al. 2013). Concerns such as global warming and environmental issues have increased the importance of sustainable manufacturing (Hu and Bidanda, 2009). Sustainable manufacturing strategies improve environmental performance of the firm which also provide competitive advantages such as low regulatory expenses on waste disposal, fines and efficiency improvements (Rondinelli and Berry, 2000).

Sustainable manufacturing leads to sustainable production practices (Greenberg and Quillian, 2010). Sustainable production as a concept was first emerged in the United Nations Conference on Environment and Development in the year 1992 (Veleva and Ellenbecker, 2001). Lowell Center for Sustainable Production (LCSP), University of Massachusetts Lowell has defined sustainable production as ‘the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people' (Veleva and Ellenbecker, 2001).

2.2.2 Sustainable Product Development

The term 'sustainable product' is originated from the concept 'sustainable development'. Sustainable product is the one that results little impact on the environment during its life cycle (Zhou et al., 2009; Ghadimi et al., 2013; Vinod and Rathod, 2010). A sustainable product has to ensure customer satisfaction, as it is essential for the success of a product and the existence of the manufacturer.

Researchers have devised tools and techniques for developing products and processes that meet environmental requirements along with customer requirements. AT&T matrix (Allenby, 2000), Environmentally Conscious Manufacturing and Product Recovery (Gungor and Guptha, 1999), QFD for environment (Masui et al., 2003), Green QFD – 2 (Zhang et al., 1999) are some techniques developed for incorporating sustainability aspects into the products.

Ljungberg, (2007) has suggested six strategies for developing sustainable products. They are 1) use materials with low environmental pollution, 2) reduced use of rare or scarce materials, 3) choose clean production process of materials, 4) avoid hazardous and toxic materials, 5) use easy recycling, easy reuse and easy degradation materials, and 6) use materials with low energy consumption. These six strategies however, do not consider social and economic aspects of sustainability.

2.3 SUSTAINABLE PRODUCT DESIGN AND ASSESSMENT TOOLS

Many research works have been carried out on Sustainable Product Development. These researches can be classified into two categories. One category is focusing on the development of tools and techniques for assessing the sustainability of an existing product and the other, developing methods for designing sustainable products (Carvalho et al., 2013). The number of tools and techniques developed to assess the sustainability of an existing product is more, compared to the quantum of methods proposed for designing sustainable new products. This is primarily due to the complexity associated with the incorporation of sustainability in the various stages of new product development such as the selection of raw materials, manufacturing processes, distribution methods, usage and the disposal of the products.

The assessment of the impact of product on all the three dimensions of sustainable development throughout the life cycle of the product is required for establishing the sustainability of the product. The tools that assess the impact of product on environment are collectively known as Simplified Life Cycle Assessment (SLCA) tools (Pigosso and Sousa, 2011). MET-Matrix (Brezet and Van Hemel, 1997), Philip Fast Five Awareness, LiDS-Wheel (Brezet and Van Hemel, 1997; Wong Yuen Ling, 2009), Eco Impact Matrix (Fargnoli and Sakao, 2008), Eco Functional Matrix (Lagerstedt, 2003), The Morphological Box (Byggeth and Hochschorner, 2006), ERPA (Graedel and Allenby, 1995), MECO (Hochschorner and Finneveden, 2003), Volvo’s List (Byggeth and Hochschorner, 2006), Eco-design Checklist (Leal-Yepes, 2013) and Ten Golden Rules (Allione et al., 2012) belong to this category. These tools are either used as product development tools or as evaluation tools for assessing the environmental impacts (Li et al., 2014). Methods such as ‘UNEP-Cleaner Production Programme’, ‘Pollution Prevention’ (Keoleian and Menerey, 1994), ‘Sustainable Product Development’ and ‘Design for Environment’ have been introduced to integrate environmental or sustainable aspects into the product development (Ardente et al., 2005).

Many researchers have conducted review of literature on eco-design tools with environmental perspectives. Ramani et al. (2010) have segregated eco-design tools into three categories. They are, tools based on Check List, Life Cycle Assessment (LCA) and Quality Function Deployment (QFD). Byggeth and Hochschorner (2006), have categorized eco-design tools as Analysis Tools (tools that can be used for assessment of environmental impacts of a product) Comparing Tools (compare different products) and Prescribing Tools (list of suggestions). Ling, 2009 have segregated environmental assessment tools into four categories namely Matrices, Checklists, Spederweb diagrams and Parametric methods. In general eco-design tools can be segregated into six categories.

First categorization of the tools is based on the assessment of indicators of sustainable development. In this category, tools based on various sustainability indicators namely economic indicators, social indicators and environmental indicators for sustainable product development are included. The second and third categorizations of tools are based on the use of Quality Function Deployment (QFD) and Check List methods respectively.

In the fourth category, tools based on spider web diagrams are included. In the fifth category, the tools based on various matrices are dealt with. In the sixth category, other types of tools along with integrated approaches have been considered. These categorizations and the important tools in these categories developed recently are explained in the succeeding sections.

2.3.1 Tools based on Sustainability Indicators

An indicator is defined as ‘variable’, ‘parameter’, ‘measure’, ‘statistical measure’, ‘a proxy for a measure’ or ‘a sub-index’ (Veleva and Ellenbecker, 2001). Ranganathan (1998) defined sustainability indicators as ‘the information used to measure and motivate progress towards sustainable goals'. Another definition for sustainable indicators is ‘a set of tools for monitoring and evaluating the compliance with a common goal to all of them, the economic development, environmental improvement and the quality of life which are essential to the application of the concept of sustainable development’ (Larsson and Martinsen, 2010).

Measurement of performance using indicators of sustainability is one of the methods to assess the sustainability level of products and the production processes. Sustainable development indicators (SDI) are generally accepted as the key measurement instruments for sustainable development (Koltun, 2010). Sustainable indicators in general simplify, quantify, analyze and communicate complex and complicated information of sustainable development by visualizing a phenomena and highlighting its trends (Singh et al., 2009).

Different taxonomy of sustainability indicators have been proposed in literatures. United Nations Commission on Sustainable Development has proposed 134 sustainable indicators categorized under 14 themes of sustainable development. These themes are poverty, governance, health, education, demographics, natural hazards, atmosphere, freshwater, biodiversity, economic development, global economic partnership, consumption, production patterns and combined land, oceans, seas and coasts (Heijungs et al., 2010).

Veleva and Ellenbecker (2001) have proposed 22 core indicators for sustainable production. These indicators are organized into six categories to address sustainable production as - energy and material use, natural environment, economic performance, community development and social justice and products. Global Reporting Initiative (GRI), a Dutch non-governmental institution has developed 79 sustainability indicators based on three dimensions of sustainable development to measure sustainability level of products (Gomes et al., 2014).

In order to compare the sustainability of products, *SocioEco Efficiancy Analysis* (*SEEbalance*) has developed a set of sustainability indicators (Clancy et al., 2013). This method assesses life cycle costs, life cycle environmental impacts and social effects of products for comparison. The choices of sustainability indicators have a significant effect on impact assessment of products. Roca (2012) has identified a total of 585 indicators based on a content analysis of 94 Canadian corporate sustainability reports. These indicators are classified according to the dimensions of sustainability - economic, environmental and social. Lal (2011) proposed a potential set of nine criteria and 37 sustainability indicators encompassing ecological, economic and social principles.

Azapagic and Perdan (2000) have developed a framework of sustainable development indicators. This study brings out the necessity for conducting case studies to identify indicators based on the nature of industries. It emphasized the need of a standard methodology with a generic set of indicators that enable comparison between different industries. According to Azapagic (2004), integration of two or more indicators of sustainability to inter-relate different aspects of sustainability is considered as an acceptable approach, as it reduce the number of indicators to a manageable number.

Assessments of environmental impacts of products are generally carried out either by quantitative or qualitative methods (Pigosso and Sousa, 2011). Quantitative methods use various environmental impact indicators for assessing environmental burdens generated by the products (Abdalla et al., 2012). The indicators which assess all the three dimensions of sustainability have to be considered for assessing the sustainability level of products. According to Gomes et al. (2014), sustainable indicators relating to three dimensions of sustainable development are used to measure progress towards and away from sustainability.

There were many studies focusing on the identification of sustainably indicators. It is difficult to propose a set of sustainability indicators, applicable to industry as organizations in the industry have different business activities (Veleva and Ellenbecker, 2002). This is one of the reasons for the abundance of sustainability indicators proposed in the literature.

2.3.2 Tools based on Quality Function Deployment

QFD is a product design tool that translates customer requirements into technical requirements for the design and production of customer satisfying products (Akao, 1990). In QFD, voice of customers are converted into technical requirements or engineering requirements using four matrices namely product planning matrix, part planning matrix, process planning matrix and product/operations planning matrix (Karsak et al., 2002).

QFD has been modified by many researchers to design environmental friendly products. A tool namely Green QFD-II was developed by Zhang et al. (1999) to integrate environmental and cost issues to QFD matrices (Puglieri et al., 2011). In Green QFD-II method, customer requirements, costing requirements and environmental requirements are included in QFD for product development processes. It also integrates sustainability assessment tools such as Life Cycle Assessment and Life Cycle Costing into the QFD.

Another tool developed based on QFD is the QFD for Environment method (Masui et al., 2003). In this method, environmental requirements are incorporated in QFD. A correlation matrix is developed between voices of environment and engineering metrics. The effect of design improvements on engineering metrics is translated to environmental quality requirements (Masui et al., 2003). Kaebernick et al. (2003) have proposed another tool namely ECQFD. In ECQFD matrix, customer requirements related to environmental issues are unearthed by specific elaboration process interviews. Customers are made aware of the environmental issues and then their specific requirements on these environmental issues are taken as customer requirements.

A number of different QFD matrices have been developed recently. Green QFD (Pusporini et al., 2013), Eco-QFD (Kuo et al., 2009), integrated LCA and House of quality in QFD (Bowea and Wang 2003), Green QFD – 3 and 4, QFD Centered method (Sakao 2007), are some of them.

Various decision support tools such as Analytic Hierarchy Process, Fuzzy AHP and Analytic Network Programming method also have been integrated with QFD. These type of integration help QFD type tools to overcome the disadvantages of existing QFD techniques such as, imperfection in setting target value, ill-defined relationship and inappropriate inclusion of company’s strengths (Poel, 2007; Dikmen et al., 2005).

2.3.3 Tools based on Check list methods

Tools based on **c**heck list methods are used to design environmental friendly products by answering a series of systematically formulated questions (Keoleian and Menery, 1994). Eco-design checklist (Brezet and Van Hemel, 1997), Eco-estimator (Tischner et al., 2000), Phillips's fast five checklist (Pigosso and Sousa, 2011) are some of the checklists developed by researchers. These methods help to impart environmental requirements into products. The designer should acquire adequate knowledge about the product's life cycle and its environmental impacts. Some of these checklist based tools are described in the succeed ding paragraphs.

Eco-design checklist method developed by Hans Brezet and Caroline van Hemel is intended for reducing environmental impact of product in product development (Tischner et al., 2000; Brezet and van Hemel, 1997). Another tool named ABC-Analysis is developed for categorizing the intensity of environmental impact into A, B and C categories on predefined criteria. The main advantage of this method is that it encompasses all the three elements of sustainability (Tischner et al., 2000). Eco-Indicator 99 method proposed by Dehghanian and Mansour (2009) weighs environmental damages caused by the product in three categories namely human health, ecological quality and resource consumption. A panel of experts estimates these damages with 40%, 40% and 20% weights respectively for each category. The scores obtained for different environmental damages are then combined to get one single score.

Researchers are of the opinion that the check list methods were obsolete, as there was no commonly agreed procedure for the same (Jungbluth et al., 2012). In addition, economic part of sustainability in usage and end of life stages are not considered in most of the check lists.

2.3.4 Tools based on Spider Web Diagrams

Environmental impacts of products can be graphically represented in spider web diagrams. Quick reviews of product on its environmental impacts are possible with this method. This method uses a qualitative approach which causes its widespread use in comparing products of similar kind.

One of the spider web diagrams ‘Eco-compass’ is used for assessing environmental impact. In Eco-compass all ecological aspects are encompassed in six dimensions namely service extension, revalorization, mass intensity, resource conservation, health risk and environmental risk (Byggeth and Hochschorner, 2006). LiDS-Wheel is another spider web diagram developed by Caroline van Hemel and Hanz Brezet for UNEP Eco-design Manual (Pigosso and Sousa, 2011). LiDS-Wheel comprises of 8 eco-design improvement strategies as eight axis of a wheel. These eight axes are new concept development, selection of low impact material, reduction of material usage, optimization of production techniques, optimization of distribution system, optimization of initial life time and reduction of impact during use.

Spider web diagrams are basically qualitative assessment tools that provide options on environmental performance of product to the practitioner. This method is widely accepted due to its clarity in application and quick to estimate. Scoring system used in this type tools are simple to understand and apply (Lagerstedt, 2003).

2.3.5 Tools based on Matrices

Matrix methods present options and importance of the options as the rows and columns of a matrix to assess the environmental impact on different aspects of product design and manufacturing. Different matrix methods have been developed to assess the environmental impact of products and also to compare alternative options. These methods are simple to use and understand, as most of these methods are two dimensional. The matrix methods based on qualitative and semi quantitative data have been developed by the researchers for different types of applications.

The matrix methods proposed based on the qualitative data are Leopold matrix (Leopold et al., 1971), Boeing Process Environmental Matrix (Eagen and Weinberg, 1997), AT & T matrix (Graedel 1995), Environmental Design Strategy Matrix (Lagerstedt, 2003), Eco-Impact Matrix (Fargnoli and Sakao, 2008) and Eco-functional Matrix (Lagerstedt, 2003). DfE Matrix (Yarwood and Eagen, 2009), MET Matrix (Byggeth and Hochschoerner, 2006), MECO Matrix (Wenzel et al., 1997) are some of the matrices developed which uses semi quantitative data.

Leopold et al. (1971), proposed an environmental impact matrix for impact assessment of the alternatives for product development. The first activity in this method is to test the effect of the proposed alternative on environment. Secondly, importance of these effects is evaluated for each alternative. Thirdly, the total magnitude of the effect is found out for each alternative proposed. The matrix is developed in such a way that one axis represents the actions that cause environmental impacts where as the other axis represents the environmental impacts. The importance of causes and impacts are rated in a scale of 1to10.

MET Matrix is another simplified life cycle analysis tool that analyzes environmental impact of a product over its life cycle. MET stands for Materials, Energy and Toxicity. In this method environmental issues are categorized under Material cycle, energy used, and toxic emission (Brezet and van Hemel, 1997). It provides an overall idea about areas of improvement required for the product. MET Matrix analyzes the raw materials, energy consumed and toxic emissions at its life cycle stages- extraction, production, manufacturing, distribution, utilization (operation and serving), and end of life (recovery and disposal) of the product.

Another technique, MECO Matrix, is developed by the Danish Institute for product development and dk-TEKNIK. MECO stands for Materials, Energy, Chemicals and Others (Wenzel et al., 1997). For each material, energy, chemicals and others used for the product and all inflows and outflows are assessed for each stage of the life cycle. Comparison of products is carried out by assessing each category based on the consumption of resources (Hochschorner and Finneveden, 2003).

In Eco-functional matrix (Lagerstedt, 2003), functional requirements and environmental impacts are evaluated in the design stage of product development. In this method, eco-performances are optimized by continual feedback (Hauschild et al., 2008). The matrix establishes a communication platform between the functional priorities and environmental impacts. The functional priorities are the physical utilities, reliability, safety, economy, technical feasibility, while environmental impact is assessed based on scarce material, toxic material and energy consumed.

Fargnoli and Sakao (2008) have developed a matrix named Eco-Impact Matrix. It is used to identify the improvement areas of a product in the different stages of life cycle. A pilot programme is conducted to prioritize the improvement areas. Priorities of improvement and life cycle phases are juxtaposed against each other and based on risk for implementation, a score between 0 to 1 is given. High risk and low risk areas can be visually seen in the matrix (Fargnoli and Sakao 2008).

DfE Matrix developed by Yarwood and Eagen is for comparing products based on the quality of design by evaluating materials, energy used, liquid, gaseous and solid residue generated throughout the production process from pre-manufacture to end of life. As many as 100 questions on a wide range of effects are asked to assess the design and environmental issues at different stages life cycle (Yarwood and Eagen, 2009).

Another technique namely AT & T (ERPA) Matrix is developed by Graedel and Allenby as a semi-quantitative LCA method (Graedel and Allenby, 1995). This method helps organizations to improve their environmental performances by evaluating products, processes, facilities, services, and infrastructure. Product sustainability index proposed by Jaafer et al. (2007) is another method to measure environmental impact of a product. Designer records a score for each influencing factor at different stages of product life cycle in a matrix, where sustainability components are taken in one direction and life cycle stages in the other direction (Jayal et al., 2010).

In the matrix methods of evaluation, the arrangement of the rows and columns in matrix can be done according to the factors required to be considered for a particular product. This flexibility makes it an acceptable tool for the sustainability analysis (Keolian and Menery, 1994). Organization of data in these matrices is also easy to carry out, as it is arranged in two dimensional matrixes. Since the information presented in matrices is consistent, designer can easily compare the relationships between products and the environmental impacts caused by these products (Keolian and Menery, 1994).

2.3.6 Tools based on Integrated Approaches

The sustainability of products is assessed using integrated approaches where environmental, social and economic assessments are carried out simultaneously. This approach has gained acceptance due to the reason that the sustainable products have to be environmentally, economically as well as socially acceptable. Assessment on all the three dimensions of sustainability is essential for a product to be sustainable and successful in the market as well.

Yuan et al. (2012) have proposed a three dimensional system approach which considers technology, energy and material as main components to implement pollution prevention strategies that improve sustainability performance of manufacturing systems. LCA is a step ahead to evaluate environmental effects of a product, process or an activity throughout its life cycle or lifetime, which is also known as a ‘cradle to grave’ analysis (Roy et al., 2009).

The method, ‘Sustainable Recovery Network’ proposed by Dehghanian and Mansour (2009), is used to achieve a balance between economic, environmental and social impacts by integrating Life Cycle Assessment (LCA) and Analytical Hierarchy Process (AHP). Kuick et al. (2011) have explored the post use stage of product life cycle to increase utilization of the products by employing 6Rs methodology along supply chains. 6R methodology analyses the impact on the six aspects namely reduce, recover, redesign, reuse, recycle and remanufacturing and estimates a score for comparison.

The Society for Environmental Toxicology and Chemistry (SETAC) considers three dimensions of sustainable developments through a combined approach of environmental life cycle assessment, life cycle costing and social life cycle assessment for life cycle assessment of products (Clancy et al., 2013). Eco-quality function deployment (Eco-QFD) proposed by Kuo et al. (2009), used fuzzy group method to introduce environmental concerns in QFD, for reducing vagueness and uncertainty in group decision making processes. The objective of this method is to help the organizations produce environment friendly products along with satisfying customer requirements.

Heijungs et al. (2010) presented a framework that incorporates different models for analyzing the environmental aspects along with economic and social aspects of sustainability in conjunction with life cycle analysis. Fargnoli and Sakao, (2008) developed an Eco Design Pilot tool to derive the design characteristics of a product that has better environmental performance. This tool helps in prioritizing the improvement areas of a product through a pilot program named Eco-Impact Matrix (EIM) to identify the area where the need of improvement is high.

Hassan et al. (2012) has developed an Integrated Morphological Analysis – Analytic Hierarchy Process (MA-AHP) approach for decision making. Morphological Analysis (MA) is integrated with Analytical Hierarchy Process (AHP) for assessing the sustainability index of alternative design solutions. In this approach all the three dimensions of sustainability are considered for calculating the index.

In Integrated ECQFD and LCA method, two separate tools namely ECQFD and LCA are integrated for sustainable new product development. In this method environmental requirements are converted as customer requirements and the relative weights of these requirements are assessed and compared for the different design options (Vinod and Rathod, 2010).

In integrated type of tools, one or more existing tools, techniques or methods are integrated for product design/assessment. These types of tools combine the advantages of both the tools. Researches on integration of different tools for sustainability and deriving the benefits of environmental assessment tools for the product development process are still in a developing stage (Baumann et al. 2002).

2.4 TAXONOMY OF SUSTAINABLE PRODUCT DESIGN AND SUSTAINABILITY ASSESSMENT TOOLS

Many tools and techniques for sustainable product development and sustainability assessment have been developed during the past two decades. A detailed literature review was carried out to classify these existing tools, techniques and methods that deal with sustainable product development, design and assessment. The initial search with key words ‘sustainable product development tools’ was resulted in 17 tools. The key word was then changed to ‘eco design tools’ and the search was resulted in 29 tools. These 29 tools were studied elaborately and the taxonomy of these tools was carried out.

2.4.1 Categorization of Product design/assessment tools based on three dimensions of sustainable development

The tools and techniques used for sustainable product development and sustainability assessment were studied carefully. The 29 tools identified were classified into the following seven categories. These categories are the following:

1) The tools that reckon environmental factors
2) The tools that reckon social factors
3) The tools that reckon economic factors
4) Integrated tools that reckon economic & environmental factors
5) Integrated tools that reckon economic & social factors
6) Integrated tools that reckon environmental & social factors
7) Integrated tools that reckon environmental, social & economic factors.

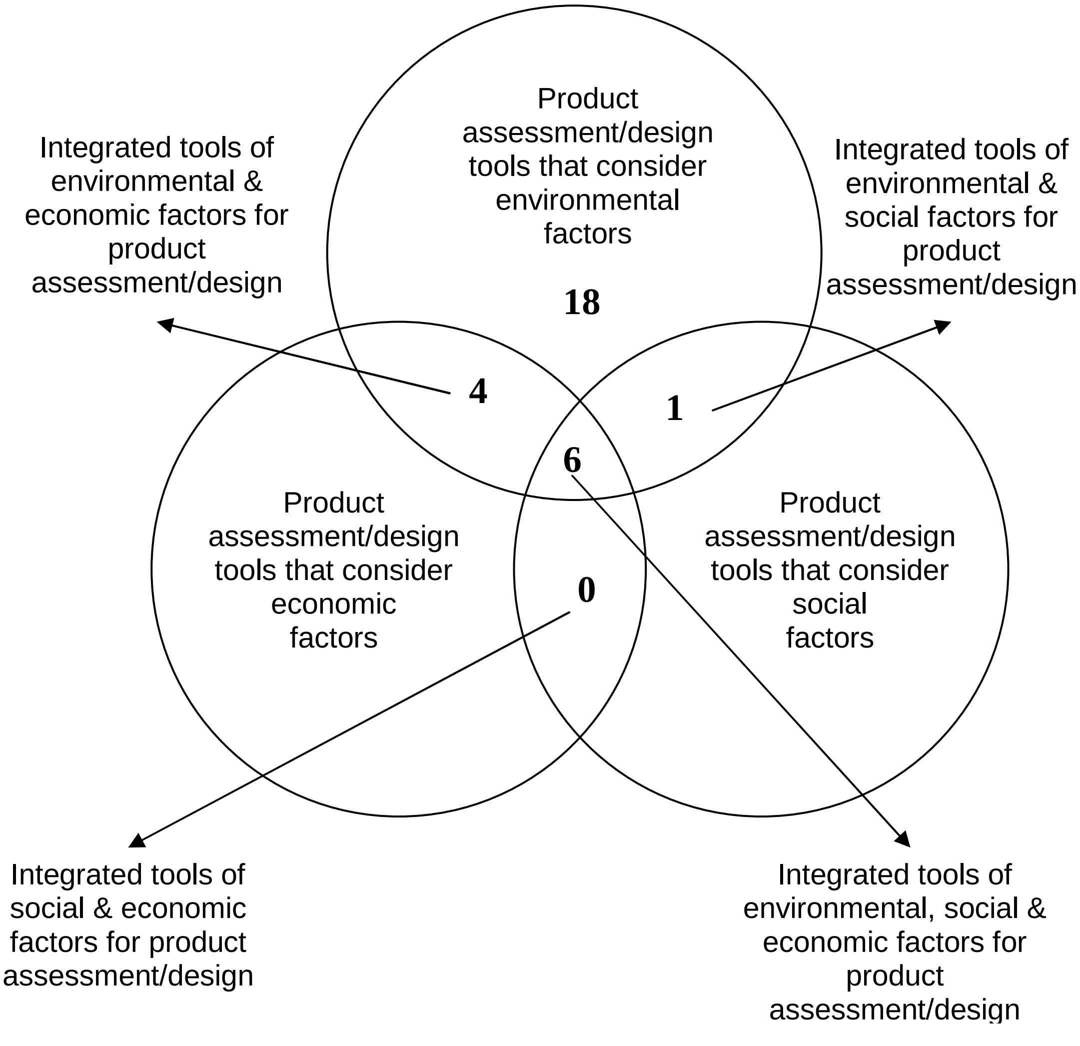


Figure 2.2 Categorization of sustainable development tools and methods based on three dimensions of sustainability

The Venn diagram presented in Fig. 2.2 depicts this categorization, with the number of tools that comes under each category. The details of tools and the authors proposed these tools in each category are described in the following paragraphs.

A total of 18 tools were identified under the category of product assessment/design tools that consider environmental factors alone. Table 2.1 shows all the tools that consider the environmental dimension for the assessment of sustainability. The first work reported was by Leopold et. al. in the year 1971. However, concentrated efforts for developing the tools in the environmental dimension were started in 1990s. This is dues to the increased awareness on the protection of the environment during that period. MET matrix developed by Brezet and Van Hemel (1997) was an important step in this regard.

As depicted in Table 2.2, a total number of 10 tools were identified in the category of product assessment/design tools that consider economic factors. Out of this, 4 tools are deal with economic aspects in combination with environmental aspects of sustainable development. One of such attempts was initially made by Brezet and Van Hemel in the year 1997 through LiDS Wheel developed for United Nations Environment Programme.

Table 2.1
Tools and methods that considers environmental factors of sustainability

Serial Number	Authors	Name of tool/method
1	Leopold et al., 1971	Leopold Matrix
2	Graedel and Allenby, 1995	Environmentally Responsible Product Assessment
3	Brezet and Van Hemel, 1997	MET Matrix
4	Wenzel et al., 1997	Environmental Design of Industrial Products
5	Brezet and Van Hemel, 1997	LiDS Wheel
6	Yan et al, 2002	Eco-Compass
7	Zhang et al., 1999	Green Quality Function Deployment 2
8	Ritthoff et al., 2002	Material Input per Service Unit
9	Masui et al., 2003	Quality Function Deployment for Environment
10	Lagerstedt, 2003	Eco-Functional Matrix
11	Hochschorner and Finneveden, 2003	MECO Matrix
12	Kaebernick et al., 2003	Environmentally Conscious Quality Function Deployment method
13	Khan et al., 2004	Lin X
14	Howarth and Hadfield, 2006	Sustainable product design
15	Byggeth and Hochschorner, 2006	ABC Analysis
16	Sakao, 2007	QFD-centered design methodology
17	Kasarda et al., 2007	Design For Adaptability (DFAD)
18	Jaafer et al., 2007	Product sustainability Index
19	Fargnoli and Sakao, 2008	Eco-impact Matrix
20	Yarwood and Eagen., 2009	Design for Environment Matrix
21	Vinod and Rathod, 2010	Integrated Environmentally Conscious Quality Function Deployment & LCA method
22	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
23	Garbie, 2012	Design for Sustainable Manufacturing Enterprises (DFSME)
24	Hassan et al., 2012	MA-AHP approach
25	Jungbluth. , 2012	Eco-indicator 99
26	Pusporini et al., 2013	Integrating environmental requirements into Quality Function Deployment (QFD)
27	Ziout et al., 2013	Multi-criteria decision support tool
28	Romli et al., 2014	Integrated eco-design decision making (IEDM)
29	Gaha et al., 2014	Eco-designing of products based on feature technology

Seven tools that consider social factors of sustainable development are shown in Table 2.3. Similar to the case of economic aspects, no specific tool was identified that mull over social factor of sustainable development alone. One tool that considers social aspects in combination either with environmental aspects was also identified. The low number of tools in these categories is mainly due to the low contribution of social aspects as compared to economic and environmental aspects of sustainability (Despeisse, 2012). According to Hauschild et al. (2008) very little efforts has been made so far for achieving social sustainability at manufacturing level, which is very important for attaining a total sustainable development.

Table 2.2
Tools and methods that considers economic factors of sustainability

Serial Number	Authors	Name of tool/method
1	Zhang et al., 19 99	Green Quality Function Deployment 2
2	Lagerstedt, 2003	Eco-Functional Matrix
3	Khan et al., 2004	Lin X
4	Howarth and Hadfield, 2006	Sustainable product design
5	Jaafer et al., 2007	Product sustainability Index
6	Brezet and Van Hemel, 1997	LiDS Wheel
7	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
8	Hassan et al., 2012	MA-AHP approach
9	Ziout et al., 2013	Multi-criteria decision support tool
10	Romli et al., 2014	Integrated eco-design decision – making (IEDM)

As many as 10 tools consider environmental and economic aspects of sustainability. These tools are listed in Table 2.4. Table 2.5 shows the list of the tools that consider social and environmental aspects together. There are six tools that consider all the three dimensions of sustainable development. These tools are shown in Table 2.6. Product sustainability index method proposed by Jaafar et al. (2007) is one of the pioneer tools developed in this category.

Table 2.3
Tools and methods that considers social factors of sustainability

Serial Number	Authors	Name of tool/method
1	Yan et al, 2002	Eco-Compass
2	Khan et al., 2004	Lin X
3	Howarth and Hadfield, 2006	Sustainable product design
4	Jaafer et al., 2007	Product sustainability Index
5	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
6	Hassan et al., 2012	MA-AHP approach
7	Ziout et al., 2013	Multi-criteria decision support tool

Table 2.4
Tools and methods that considers environmental and economic factors of sustainability

Serial Number	Authors	Name of tool/method
1	Brezet and Van Hemel, 1997	LiDS Wheel
2	Zhang et al., 1999	Green Quality Function Deployment 2
3	Lagerstedt, 2003	Eco-Functional Matrix
4	Khan et al., 2004	Lin X
5	Howarth and Hadfield, 2006	Sustainable product design
6	Jaafer et al., 2007	Product sustainability Index
7	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
8	Hassan et al., 2012	MA-AHP approach
9	Ziout et al., 2013	Multi-criteria decision support tool
10	Romli et al., 2014	Integrated eco-design decision –making (IEDM)

Table 2.5
Tools and methods that considers environmental and social factors of sustainability

Serial Number	Authors	Name of tool/method
1	Yan et al., 2002	Eco-Compass
2	Khan et al., 2004	Lin X
3	Howarth & Hadfield, 2006	Sustainable product design
4	Jaafer et al., 2007	Product sustainability Index
5	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
6	Hassan et al., 2012	MA-AHP approach
7	Ziout et al., 2013	Multi-criteria decision support tool

Table 2.6
Tools and methods that considers environmental, economic and social factors of sustainability

Serial Number	Authors	Name of tool/method
1	Khan et al., 2004	Lin X
2	Howarth & Hadfield, 2006	Sustainable product design
3	Jaafer et al., 2007	Product sustainability Index
4	Heijungs et al., 2010	A scientific frame work for sustainability life cycle analysis
5	Hassan et al., 2012	MA-AHP approach
6	Ziout et al., 2013	Multi-criteria decision support tool

2.5 RESEARCH GAPS

Study of the existing product design tools revealed many limitations of the existing tools. A detailed study of these limitations helped to identify various research gaps in the present researches. Table 2.7 exemplify various research gaps identified during the literature review

Table 2.7
Research gaps identified through the literature survey

Research Gap Observed	Remarks
The existing product development tools do not consider all the stages of product development cycle (PDC).	If all the stages of PDC are not considered, the option that was selected on one stage may not be a wise option when other stages of PDC are considered. This will not support towards a sustainable production.
The existing tools do not consider Customer Requirements (CRs) and Sustainability Requirements (SRs) separately while weighing their importance.	The importance of SRs may get reduced while comparing with CRs.
The existing tools do not give freedom for the management to supplement their policies on sustainable processes and products.	The design tools that impart sustainability/ environmental requirements into products do not give freedom to the management for a partial fulfillment of sustainability or customer requirements. As a policy of the management, SRs may not be fulfilled completely as additional cost is incurred for the same.
Most of the tools either consider CRs or one or two dimensions of SRs along with CRs, for product development.	When one or two dimensions of SRs are considered, only partial fulfillment of sustainability level is achieved.

2.6 CHAPTER SUMMARY

A survey of literature was conducted to study the evolution of sustainability principles, the different types of tools and techniques for improving sustainability and the tools that consider different dimensions of sustainability. The categorization of sustainable design and sustainability assessment tools carried out in this literature review helps the organizations to select an appropriate tool from this category for product assessment or for product design. Brief description given about these tools provides a better understanding to the practitioners about the existing tools. It was observed during the literature review that the tools that consider all the stages of product development are very few. In addition, the product development tools that reckon all the three dimensions of sustainable development do not consider the importance of all the three dimensions independently.

The literature review put forward the necessity of developing a tool that overcomes all these limitations of existing product development tools. Such a tool will help the designers to produce customer satisfying sustainable products. Even an attempt for improving sustainability in products will be highly appreciated by the public and thereby increase its brand value (Nejati et al., 2010)).

CHAPTER 3

DEVELOPMENT OF CUSTOMER AND SUSTAINABILITY REQUIREMENT EVALUATION MATRIX

3.1 PREAMBLE

Tools and methods for new product developments (NPD) have gained importance in the present business environment. Satisfying the requirements of customer was the only objective in NPD till the last two decades of 20th century. The threats such as global warming, ozone layer depletion, acidification etc, urged the designers to consider environmental requirements also in NPD. As a result, inclusion of environmental aspects into NPD became one of the requirements for developing sustainable products.

Apart from environmental aspects, social and economic aspects of sustainability also need to be included for developing and manufacturing of sustainable products. The products without having a social support and economic viability can't be survived in the market (Haes and Heijungs, 2007). In short, only a sustainable product could stay alive for a reasonable period of time in the market. A new tool named 'Customer and Sustainability Requirement Evaluation Matrix (CSRE Matrix)' is proposed in this doctoral work that helps the designers and the practicing engineers to design and produce a customer satisfying sustainable product.

3.2 ‘CSRE MATRIX’

‘CSRE Matrix’ is the tool developed as a part of this doctoral works for sustainable new product development. Using CSRE Matrix, various design, material, manufacturing, disposal, usage and distribution options in different stages of product development cycle (PDC) namely Design Selection, Material Selection, Manufacturing Process selection, Distribution Selection, Usage Selection and Disposal Selection can be identified and evaluated. It also helps in analyzing these options to derive the best option among these stages and arrive at the best method of manufacturing a sustainable product that satisfy both Customer Requirements (CRs) and Sustainability Requirements (SRs). Based on the PDC stage, CSRE Matrices are named CSRE Matrix of Design Selection, Material Selection, Manufacturing Process Selection, Distribution Selection, Usage Selection and Disposal Selection stages.

Initially the CSRE Matrix for the first stage namely Design Selection (DS) will be constructed. Subsequently, CSRE Matrices are developed for ‘Material Selection’ (MS), ‘Manufacturing Process Selection’ (MPS), ‘Distribution Selection’ (DrS), ‘Usage Selection’ (US) and ‘Disposal Selection’ (DiS) stages.

The importance of Customer Requirements (CRs) and Sustainability Requirements (SRs) will be different at each stage of product development cycle (PDC). Hence, for prioritizing CRs and SRs, a structured representation of their hierarchy is required for incorporating this importance levels in the NPD (Kasarda et al., 2007). This hierarchy is obtained by ranking. Based on the ranking, weights are assigned to each CR and SR using different methods. The methods such as Rank Order Centroid (ROC) weight method (Choi and Ahn, 2011), Analytic Hierarchy Process (AHP) method (Saaty, 1980) and Fuzzy

Analytic Hierarchy Process (FAHP) method (Chang, 1996) are used to weigh CRs and SRs. The weights assigned to each CR and SR will be used in CSRE matrices at different stages of PDC to analyze the different options for arriving at the best option.

In CSRE Matrices, each option is named as a path. For each path, a path score will be calculated based on the level of fulfillment of CRs and SRs. After developing the first CSRE Matrix - the DS Matrix, the path score obtained is carried forward to the subsequent CSRE Matrix namely, MS Matrix. Similarly, CSRE Matrices for all stages of PDC are developed. At the end of this process, the path combinations that get maximum path score will be considered as the best combination path to produce the customer satisfying sustainable product.

3.2.1 Development of CSRE Matrix

The procedure followed for the development of CSRE Matrix is shown in Fig. 3.1. It is done in two phases. The first phase of CSRE Matrix involves data collection. Data collection includes identification of CRs, SRs and engineering requirements. The CRs and SRs identified will have different importance levels that necessitate ranking and weighing them against each other.

In the second phase, actual CSRE Matrices are constructed. A product design team comprising of practicing engineers from design, production, safety, quality control departments will be generally constituted for constructing these two phases of CSRE Matrix in an organization.

3.2.1.1 CSRE Matrix phase-1

The first Phase of CSRE Matrix involves 9 steps. The objective of first phase is to identify CRs and SRs and to weigh them based on their importance level. The activities to be carried out in these steps are explained in subsequent sections.

Step 1: Identify product, components and PDC stages

Once the product is selected for developing the CSRE Matrix, its components are identified subsequently. For each component, the stages of PDC that need to be analyzed are decided by the design team. Stages of PDC generally considered are ‘Design Selection’ (DS), ‘Material Selection’ (MS), ‘Manufacturing Process Selection’ (MPS), ‘Usage Selection’ (US), ‘Disposal Selection’ (DiS) and ‘Distribution Selection’ (DrS). Construction of all the stages of PDC may not be required for all components.

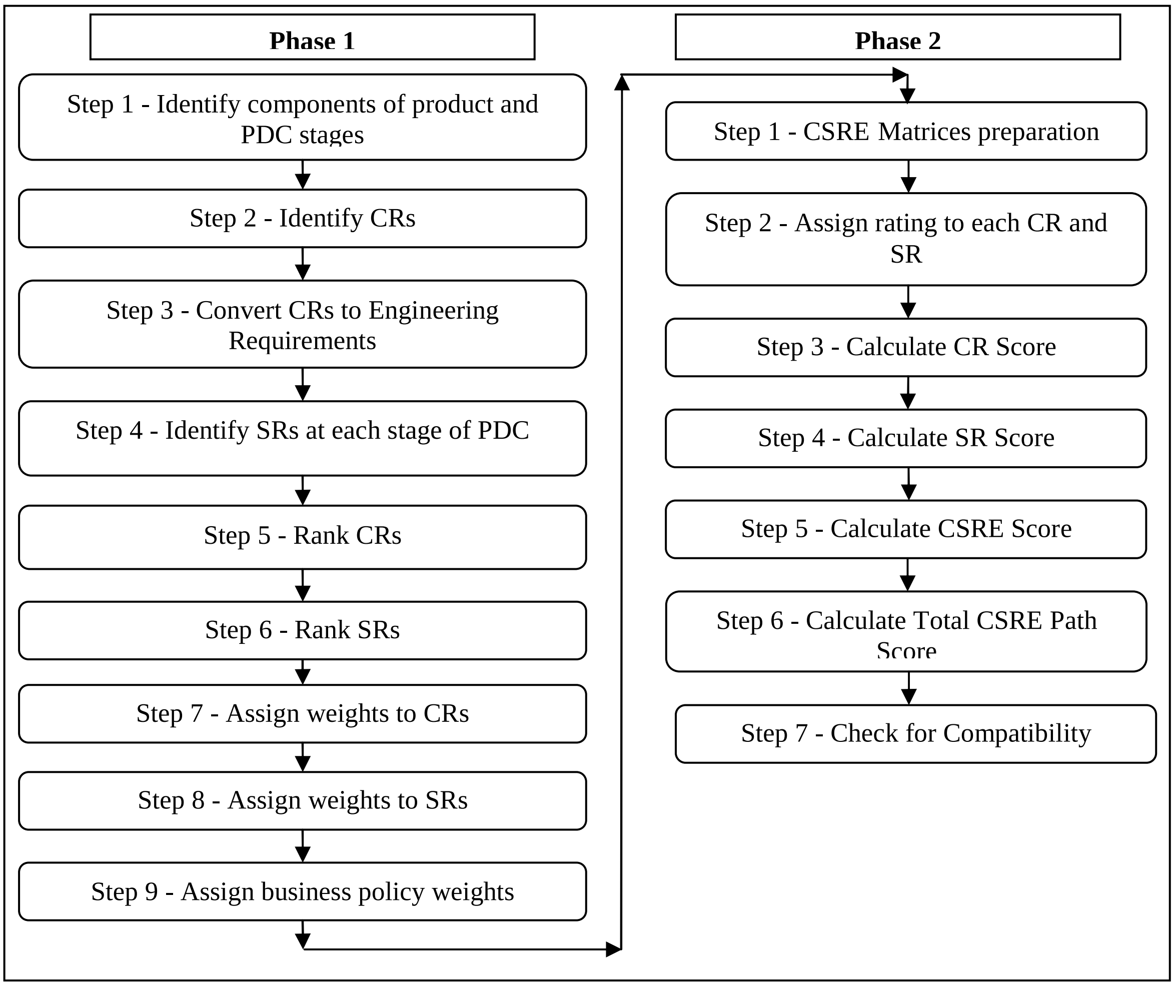


Figure 3.1 CSRE Matrix Developments in Two Phases

Step 2: Identify CRs

Identification of various CRs of the components of the product is the second step to be carried out. The design team constituted for the CSRE Matrix development acquires CRs from the history of various enquiries, company standards, market survey and by using other probable sources. Brainstorming technique (Osborn, 1957) among the design team is also carried out to collect the CRs. The CRs identified are subsequently segregated as requirements under each stage of PDC.

Step 3: Convert CRs to Engineering Requirements

CRs identified are further analyzed by the design team to derive various engineering requirements at design, material, process, distribution and usage & disposal stages. These engineering requirements are converted as possible options in the different stages of PDC. Options are the probable methods, processes or designs for fulfilling the engineering requirements of each stage of PDC. These options are termed as paths in CSRE Matrices.

Step 4: Identify SRs at each stage of PDC

The different options identified under each stage of PDC are carefully studied and analyzed by the design team to identify various SRs of the components. Brainstorming technique among the design team members is applied to find out various SRs under each stage of the PDC. The SRs identified are subsequently segregated into requirements under each stage of PDC.

Step 5: Rank CRs

CRs at all stages of PDC are taken together and ranked based on the importance in the different stages of PDC. This activity is carried out by the design team members. The most important CR shall be given the rank one. The next important CR shall be ranked two and the ranking is continued till all the CRs are ranked. Delphi method is applied among the design team members to reach a consensus on the ranking.

Step 6: Rank SRs

SRs in all the stages of PDC also have to be ranked. These rankings are carried out based on the importance of SRs at each stage of the PDC. Similar to the ranking of CRs, the most important SR shall be ranked one. The next important SR shall be ranked two and ranking continues till all the SRs are ranked. Delphi method is applied among the design team members to reach a consensus on the ranking.

Step 7: Assign weights to CRs

Ranking obtained for each CR indicates its priority among CRs. The ranks obtained are then converted into weights. Different weighing methods can be used for converting ranking into weights. ROC weights method, AHP method and FAHP are the three weighting methods generally used to carry out weighting of CRs. CSRE Matrices can be developed using any one of these methods. These methods are explained elaborately in subsequent chapters.

Step 8: Assign weights to SRs

Ranking obtained for each SR also have to be converted into weights. Similar to the weighing of CRs, SRs are also weighed using ROC weights method, AHP method and FAHP method. Detailed explanations on all these methods are included in following chapters.

Step 9: Assign Business Policy Weights

In a perfect business scenario, it would be better if CRs and SRs are given equal preferences. However, due to business constraints and competitions, organization may not be able to do the same. In such cases, weights for the CRs and SRs can be modified by the management as a policy. For modifying these weights, a new weight namely ‘Business Policy Weights (BPW)’ is included in the CSRE matrix. The level of importance of CRs and SRs can be modified using BPW. If the policy of the organisation is to take its CRs equally important as SRs, the BPW shall be equal for CRs and SRs.

3.2.1.2 CSRE Matrix phase - 2

In the second phase of the development of CSRE Matrix, the actual CSRE matrices are constructed. It is carried out in 7 steps as explained below.

Step 1: CSRE Matrix preparation

The first CSRE Matrix that has to be constructed is the DS Matrix. The structure of a CSRE Matrix is shown in Table 3.1.

The paths of the particular stage of PDC are listed in the first column of the CSRE Matrix. Various options of design are given in this column. These options are represented as option 1 to option z in Table 3.1. First row of second column starts with CRs. Various CRs identified for the DS stage are arranged in the subsequent columns. It is represented as ‘cr_1’ to ‘cr_n’ in CSRE Matrix.

Table 3.1
Structure of a CSRE Matrix

Options	CRs	cr_1	-	cr_i	-	cr_n	Total CR Score	SRs	sr_1	-	sr_j	-	sr_m	Total SR Score	PPS	CSRE Score
	Weight	v_1	-	v_i	-	v_n		Weight	w_1	-	w_j	-	w_m			
	BPW	C						BPW	D							
Option 1	Rating	x_{11}	-	x_{1i}	-	x_{1n}	crs_1	Rating	y_{11}	-	y_{1j}	-	y_{1m}	srs_1	0	$CSRE_1$
	CR Score	a_{11}	-	a_{1i}	-	a_{1n}		SR Score	b_{11}	-	b_{1j}	-	b_{1m}			
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Option k	Rating	x_{k1}	-	x_{ki}	-	x_{kn}	crs_k	Rating	y_{k1}	-	y_{kj}	-	y_{km}	srs_k	0	$CSRE_k$
	CR Score	a_{k1}	-	a_{ki}	-	a_{kn}		SR Score	b_{k1}	-	b_{kj}	-	b_{km}			
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Option z	Rating	x_{z1}	-	x_{zi}	-	x_{zn}	crs_z	Rating	y_{z1}	-	y_{zj}	-	y_{zm}	srs_z	0	$CSRE_z$
	CR Score	a_{z1}	-	a_{zi}	-	a_{zn}		SR Score	b_{z1}	-	b_zj	-	b_{zm}			

Weight assigned to each CR is entered in the second row of CSRE Matrix. It is represented as ‘v_1’ to ‘v_n’. BPW corresponding to CR given in the third row of CSRE Matrix is represented as ‘c’. Rating assigned to each option is given in the rows of the corresponding options. Step 2 explains the procedure to assign rating value to each option.

Step 2: Assign rating to each CR and SR

Rating of individual option is carried out by the design team. Members of the design team rate each option based on the level of fulfillment of each CR and SR in a Likert scale of 1 to 9. The option that fully satisfies the CR shall be given a rating of 9. The option that least satisfies the CR shall be rated as 1. The intermediate levels are chosen appropriately. SRs are also rated in the same manner as that of the CRs.

Design team analyzes these rating and check for the mismatches in individual member’s rating with the majority opinion. The design team member whose rating differs from others is asked to point out the reason for the same. These reasons are circulated through the other design team members and asked to revise ratings based on the reasons given by the member. This method continues until design team unanimously agrees on the rating for each CR and SR. The ratings are represented as ‘x_{ki}’ where k stands for the option and i stands for the customer requirement. The ratings for the combinations of option and CR are shown in Table 3.1. In the case of SRs, the ratings are represented as y_{kj} , where k represents the option and j represents the SR.

Step 3: Calculate CR Score

CR Score is calculated for each option against each CR. This score is entered in the CSRE Matrix just below the rating of the individual CR. The Score is obtained by multiplying ‘the rating of option’ with the ‘CR weight’ and ‘BPW’. This calculation is shown in Eq. 3.1.

CR Score of k^{th} option and i^{th} CR ($a_{k.i}$) = $v_i \times c \times x_{k.i}$ -------------------------- (Eq. 3.1)

Where,

v_i, c and x_{ki} represent weight of i^{th} CR , BPW of CR and rating of k^{th} option against i^{th} CR respectively.

CR Score obtained for each option against CRs are added together to obtain the overall score of that option. This score is termed as Total CR Score. This score is inserted in the CSRE Matrix just after the last CRs column. Total CR Score is calculated as shown in Eq. 3.2.

Total CR Score of option k (crs_k) $= \sum_{i=1}^{n} a_{k.i}$ -------------------------------(Eq. 3.2)

Step 4: Calculate SR Score

As in the case of CRs, SR Score is also calculated for each option against each SR. This score is obtained by multiplying 'the rating of option' with the 'SR weight' and 'BPW'. This calculation is as shown in Eq. 3.3.

SR Score of k^{th} option and j^{th} SR ($b_{k,j}$) $= w_j \times d \times y_{k.j}$ ------------------------- (Eq. 3.3)

Where,

w_j, d and y_{kj} represent weight of j^{th} SR, BPW of SR and rating of k^{th} option against j^{th} SR respectively.

SR Score obtained for each option against SR are added together to obtain the overall score of that option. This score is termed as total SR Score. This score is inserted in the CSRE Matrix just after the last SRs column. Total SR Score is calculated as shown in Eq. 3.4.

Total SR Score of option k (srs_k) $= \sum_{j=1}^{m} b_{k.j}$ ---------------------------- (Eq. 3.4)

Step 5: Calculate CSRE Score

CSRE Score is the score obtained by adding Total CR Score and Total SR Score. CSRE score is the final score of each stage of PDC against each option. This score is carried forwarded to the subsequent stage of PDC. CSRE Score calculation is as shown in Eq. 3.5.

$$\text{CSRE Score of } k^{th} \text{ option} = [\text{PPS} + \text{Total CR Score} + \text{Total SR Score}]$$

$$= [\text{PPS} + \textstyle\sum_{i=1}^{n} a_{ki} + \sum_{j=1}^{m} b_{kj}] \text{ -------- (Eq. 3.5)}$$

Where,

PPS represents Previous Path Score.

Step 6: Calculate Total CSRE Path Score

CSRE Score against an option at each stage of PDC is carried forward to the next stage as PPS. CSRE Scores in the individual rows of the last CSRE Matrix represents the Total CSRE Path Score. This Matrix also depicts all the options in the individual paths. The combination of paths which gives maximum total path score has to be selected as the best path which will produce the most customer satisfying sustainable product.

Step 7: Check for Compatibility

The options of all the stages of PDC may not be compatible with each other. Hence a compatibility checking has to be carried out by the design team. The combination of paths that obtained maximum total CSRE Path Score was initially taken for compatibility check. If these options are incompatible, the next combination of options that got the second most maximum Total CSRE Path Score should be considered for compatibility check. The process continues till the most compatible options for each component is determined.

3.3 CHAPTER SUMMARY

CSRE Matrices are constructed for selecting the best option among each stage of PDC to produce a customer satisfying sustainable product. CSRE Matrix has some similarity with the QFD. In QFD, satisfying CRs are considered most important where as in CSRE Matrices, both the CRs and SRs are considered. However, the importance to CRs and SRs are decided by the management as per their business policy.

All the three dimensions of sustainability namely economic, environmental and social dimensions have been reckoned while constructing CSRE Matrices. CSRE Matrix has many advantages as noted below.

- ‘CSRE Matrix’ reckons CRs and SRs separately while developing PDC stages.
- ‘CSRE Matrix’ weighs CRs, SRs and sub-elements of CRs and SRs.
- ‘CSRE Matrix’ assists the designer to determine the combination of the most suitable product development methods for NPD.
- ‘CSRE Matrix’ helps to carry out compatibility checks of various options for designing the components of the product.
- ‘CSRE Matrix’ helps the designer to impart business strategy in product development.
- ‘CSRE Matrix’ helps to derive alternative options in the different stages of PDC by rating them based on the fulfilment of the sub-elements of CRs and SRs.
- All the stages of PDC are analyzed in ‘CSRE Matrix’.

CHAPTER 4

CSRE MATRIX WITH RANK ORDER CENTROID WEIGHT METHOD AND ITS IMPLEMENTATION STUDY

4.1 PREAMBLE

In the process of application of CSRE Matrices for NPD, different alternatives of product development stages are evaluated and a score is arrived at, based on the fulfilment of Customer Requirements (CRs) and Sustainability Requirement (SRs). Each CR and SR has different importance level that varies depending on the nature of the product. Expressing the importance of CRs and SRs are subjective in nature. These importance levels are initially expressed by ranking. Based on the ranking, weights are assigned to each CR and SR. Rank Order Centroid (ROC) weight method is used for weighing CRs and SRs in this CSRE Matrix. The objective of developing CSRE Matrix with ROC weight method is to find out the importance weight of CRs and SRs as a preliminary simple method. ROC weights method is one of the important multi-criteria decision support tools that help converting subjective opinion into objective evaluation.

4.2 RANK ORDER CENTROID (ROC) WEIGHT METHOD

Decision-making is a process by which the best alternative is selected from a course of action, option, act or multitude of alternatives (Ahn, 2011). In order to help decision making process, Barron and Barret (1996) have proposed a weighting method called Rank

Order Centroid (ROC) Weight method that converts subjective nature of an opinion into objective nature.

The weights obtained through ROC method are generally called the centroid weights (i.e., center of mass) as it seeks to identify a single set of weights that is representative of all the possible weights combinations. Rank Order Centroid (ROC) weights formula is shown in Eq. 4.1 (Ahn, 2011). The weights calculated for 1st rank and the last rank (n) are shown in Eq. 4.2 and Eq. 4.3 respectively.

$$wt_i = \left(\frac{1}{n}\right)\sum_{j=i}^{n}\left(\frac{1}{j}\right) \text{-------------------------------} (Eq\,4.1)$$

$$wt_1 = \left(1+\frac{1}{2}+\frac{1}{3}+\ldots\frac{1}{n}\right)/\,n \text{---------------------------} (Eq\,4.2)$$

$$wt_n = \left(\frac{1}{n}\right)/\,n \text{---------------------------------} (Eq\,4.3)$$

Where,
i = 1, 2, ……, n.

‘*Wt*$_i$’ represents the weight of ith rank and ‘n’ represents the total number of attributes that are ranked.

Many researchers are of the opinion that ROC weights method is superior to other decision making approaches such as AHP and Fuzzy methods. Noh and Lee, (2003) reported that the simplicity and ease of use of ROC weights make it a practical method for determining criteria weights while comparing ROC weights method with AHP and fuzzy method. Also, Srivastava et al. (1995) have compared different weight elicitation methods and found that ROC weights are superior to other methods. According to Yager et al. (2011), ROC weights method is well applicable and acceptable when weights are to be assigned by asking simple questions to a decision maker. This method is used to assign weights to an attribute when approximation is needed (Wei et al., 2013).

4.3 IMPLEMENTATION OF CSRE MATRIX USING RANK ORDER CENTROID (ROC) WEIGHTS METHOD

A case study on the implementation of the CSRE Matrix was conducted in a plastic bottle manufacturing firm, M/s Duropack Industries, located at Mundur Industrial Estate in Kerala State, India. Duropack manufactures PET (Polyethylene Terephthalate) and High Density Polyethylene (HDPE) bottles for filling carbonated soft drinks, mineral water, fruit juices, edible oil etc.

The management of the company was interested in developing environmental friendly products. Upon contacting the top management, they gave their consent for conducting the case study in the company. The R&D department of M/s Duropack was explained about CSRE Matrix and sought their involvement in conducting the case study. A design team comprising of Design Engineer, Quality Control Engineer and Safety Engineer was constituted by the top management to use the CSRE Matrix for NPD. Implementation of CSRE Matrix was carried out in two phases. These two phases are explained in the subsequent sections.

4.3.1 CSRE Matrix Phase-1

Phase-1 of CSRE Matrix involved 9 steps. These nine steps were followed for the identification and weighing of CRs and SRs. These steps were carried out as described below.

Step 1: Identify product, product’s components and PDC stages

After the discussions and consultation with the managers and executives of Duropack, 500 ml container bottle for edible oil was selected as the product for conducting the case study. 500 ml bottles were having high production rate and demand. The producers of edible oil are the major customers for 500 ml bottles.

Design of the plastic bottle is being very simple and the aesthetic of the product does not change with a single design, DS stage was not considered in the case study. Since the usage and disposal of the products were not within the control of the organization, US and DiS stages of PDC also were not considered. With that, the CSRE Matrices corresponding to MS, MPS and Drs stages of PDC were constructed in this case study.

Step 2- Identify CRs

Identification of various CRs of 500 ml bottle is the second step carried out in the CSRE Matrix. The design team collected CRs from the history of various enquiries, company standards and market survey on design, cost, standard, safety, material selection, manufacturing process, distribution, usage and disposal of the product.

Further, after an elaborate discussion with edible oil manufacturers, the design team identified the major CRs of the 500 ml bottle. They were low raw material cost, high impact load, excellent barrier to UV rays, excellent surface finish, low production cost, uniform wall thickness, high durability, high temperature resistance, low packing cost and low distribution cost. The CRs identified are subsequently segregated into the requirements of different stages of PDC. Table 4.1 shows the CRs identified and their segregation under different stages of product development.

Table 4.1
Customer Requirements

Sr. No.	Customer Requirements	Abbreviation	Stages of PDC
1	Low Raw Material Cost	RMC	Material Selection
2	High Impact Load	HIL	
3	Excellent Barrier Property against UV	EBP	
4	Excellent Surface Finish	ESF	Process Selection
5	Low Production Cost	LPC	
6	Uniform Wall Thickness	UWT	
7	High Durability	HDR	Distribution Selection
8	High Temperature Resistance	HTR	
9	Low Packing Cost	LPAC	
10	Low Distribution Cost	LDC	

Step 3 – Convert CRs to engineering requirements.

CRs identified in the second step were analyzed by the design team to find the corresponding engineering requirements as the possible alternatives in Material Selection (MS), Manufacturing Process Selection (MPS) and in the Distribution Selection (DrS) stages of PDC. Design team then identified possible alternatives in each stage of PDC for fulfilling these engineering requirements. High Density Poly Ethylene (HDPE) and Poly Ethylene Terephthalate (PET) were the two options of materials under MS stage of PDC. Similarly, other options against each stage of PDC were also found out. Table 4.2 depicts different PDC stages and the options that were identified by the design team.

Table 4.2
PDC Stages, Options and Customer Requirements

Stages	Options	Customer Requirements
Material Selection	HDPE	Low Raw Material Cost, High Impact Load, Excellent Barrier to UV Rays
	PET	
Manufacturing Process Selection	Injection Moulding	Excellent Surface Finish, Low Production Cost, Uniform Wall Thickness
	Injection Moulding and stretch blow moulding	
	Extrusion Blow Moulding	
Distribution Selection	Economic Bag Packing (EBP)	High Durability, High Temperature Resistance, Low Packing Cost, Low Distribution Cost
	Standard Special Packing (SSP)	

Step 4: Identify SRs for each PDC.

The nature of engineering requirements and various options to fulfill these requirements were carefully studied by the design team to identify various SRs. These SRs were segregated as the requirements of different stages of PDC. Table 4.3 shows various SRs identified by the design tam and their segregation under different stages of product development.

Step 5: Ranking of CRs

CRs of all stages of PDC were put together and ranked by the design team. Ranking were carried out based on the importance of the CR in each stage of the PDC. The most important CR has been given rank one. The next important CR has been ranked two and the ranking has continued till all the CRs were ranked. CRs and their rankings are shown in Table 4.4.

Table 4.3
Sustainability Requirements

Sr. No.	Sustainability Requirements	Abbreviation	Stages of PDC
1	More Recyclable	MRC	Material Selection
2	Low breakdown when exposed to ultra violet	BUV	
3	Low content of additives	LCA	
4	Low Material Waste	LMW	Process Selection
5	Low Packing Waste	LPW	Distribution Selection

Table 4.4
Ranks of Customer Requirements

Sr. No.	Description	Abbreviation	Rank	Stages of PDC
1	Low Raw Material Cost	RMC	1	Material Selection
2	High Impact Load	HIL	5	
3	Excellent Barrier to UV Rays	EBP	6	
4	Excellent Surface Finish	ESF	8	Process Selection
5	Low Production Cost	LPC	2	
6	Uniform Wall Thickness	UWT	9	
7	High Durability	HDR	7	Distribution Selection
8	High Temperature Resistance	HTR	10	
9	Low Packing Cost	LPAC	3	
10	Low Distribution Cost	LDC	4	

Step 6: Ranking of SRs

SRs of all stages of PDC were also ranked by the product design team. These rankings were carried out based on the importance of SRs under each stage of the PDC. The most important SR has been ranked one. The next important SR was ranked two and ranking was continued till all the SRs were ranked. SRs and their rankings are shown in Table 4.5.

Step 7: Assign weights to CRs

Ranking obtained for each CRs indicates their priority level. These rankings were then converted into weights. ROC weights method has been used for weighting these ranked customer requirements. Weights were arrived at using the ROC weights calculation formula depicted in equation 4.1. CRs and their weights are shown in Table 4.6.

Table 4.5
Ranks of Sustainability Requirements

Sr. No.	Description	Abbreviation	Rank
1	More Recyclable	MRC	1
2	Less breakdown when exposed to ultra violet	BUV	3
3	Less content of additives	LCA	2
4	Low Material Waste	LMW	4
5	Low Packing Waste	LPW	5

Step 8: Assign weights to SRs

Similar to the weighting of CRs, ROC weights method was applied for weighing the SRs. For this, all the SRs were ranked based on their importance level at each stage of PDC. SRs and their weights calculated based on ROC weight method are shown in Table 4.7.

Table 4.6
Weights of Customer Requirements

Sr. No.	Description	Abbreviation	Rank	Weights
1	Low Raw Material Cost	RMC	1	0.29
2	High Impact Load	HIL	5	0.08
3	Excellent Barrier to UV Rays	EBP	6	0.06
4	Excellent Surface Finish	ESF	8	0.03
5	Low Production Cost	LPC	2	0.19
6	Uniform Wall Thickness	UWT	9	0.02
7	High Durability	HDR	7	0.05
8	High Temperature Resistance	HTR	10	0.01
9	Low Packing Cost	LPAC	3	0.14
10	Low Distribution Cost	LDC	4	0.11

Table 4.7
Weights of Sustainability Requirements

Sr. No.	Description	Abbreviation	Rank	Weights
1	More Recyclable	MRC	1	0.46
2	Low breakdown when exposed to ultra violet	BUV	3	0.16
3	Low content of additives	LCA	2	0.26
4	Low Material Waste	LMW	4	0.09
5	Low Packing Waste	LPW	5	0.04

Step 9: Assigning Business Policy Weights

In this case study, CRs and SRs were given equal preferences. Hence, Business Policy Weight to CRs and Business Policy Weight to SRs were given weights of 0.5 each.

4.3.2 CSRE Matrix phase 2

In the second phase of CSRE Matrix, the actual CSRE Matrices were constructed. This phase included 7 steps as explained in chapter 3. The first CSRE Matrix constructed was Material Selection Matrix and is shown in Table 4.8. The input into the first column of CSRE Matrix was the various options of materials identified. These options were HDPE and PET.

Table 4.8
Material Selection Matrix

Material Selection Matrix												
Material Option	CRs	EBP	RMC	HIL	Total CR Score	SRs	MRC	BUV	LCA	Total SR Score	PPS	CSRE Score
	CR Weight	0.06	0.29	0.08		SR Weight	0.46	0.16	0.26			
	BPW	0.50				BPW	0.5					
HDPE	Rating	8.00	6.00	6.00	1.39	Rating	9.00	8.00	9.00	3.84	0	5.23
	CR Score	0.26	0.88	0.25		CR Score	2.06	0.63	1.16			
PET	Rating	6.00	8.00	7.00	1.66	Rating	6.00	4.00	2.00	1.94	0	3.60
	CR Score	0.19	1.17	0.30		CR Score	1.37	0.31	0.26			

The CRs identified in this stage were ‘Low Raw Material Cost’, ‘High Impact Load’ and ‘Excellent Barrier to UV Rays’ and their corresponding weights calculated were 0.06, 0.29 and 0.08 respectively. The SRs in the MS stage were ‘More Recyclable’, ‘Low breakdown when exposed to ultraviolet rays’ and ‘Low Content of Additives’. The corresponding weights calculated were 0.46, 0.16 and 0.26. Ratings for each CRs and SRs were carried out by the design team.

Table 4.9
Manufacturing Process Selection Matrix

Manufacturing Process Selection Matrix											
Material Option	Process options	CRs	ESF	LPC	UWT	Total CR Score	SRs	LMW	Total SR Score	PPS	CSRE Score
		Weight	0.03	0.19	0.02		Weight	0.09			
		BPW	0.50				BPW	0.50			
HDPE	Injection molding	Rating	9.00	6.00	9.00	0.82	Rating	8.00	0.36	5.23	6.41
		CR Score	0.15	0.58	0.10		CR Score	0.36			
	Extrusion Blow Molding	Rating	6.00	8.00	6.00	0.94	Rating	6.00	0.27	5.23	6.43
		CR Score	0.10	0.77	0.06		CR Score	0.27			
PET	Injection molding	Rating	9.00	6.00	9.00	0.82	Rating	8.00	0.36	3.6	4.79
		CR Score	0.15	0.58	0.10		CR Score	0.36			
	Injection molding & Stretch Blow Molding	Rating	8.00	7.00	8.00	0.89	Rating	8.00	0.36	3.6	4.86
		CR Score	0.13	0.68	0.08		CR Score	0.36			
	Extrusion Blow Molding	Rating	7.00	5.00	6.00	0.66	Rating	6.00	0.27	3.6	4.53
		CR Score	0.12	0.48	0.06		CR Score	0.27			

In the case of Business Policy Weight, equal importance has been given to CRs and SRs in all the paths. MPS Matrix and DrS Matrix were also developed. These two matrices are shown in Table 4.9 and Table 4.10 respectively. The last column in Table 4.10, DrS Matrix indicates the CSRE Score for the different options considered in the three stages of PDC. The highest value obtained is 7.14 which correspond to combination path with material as HDPE, process as extrusion blow moulding and distribution using economic bag packing. Since this combination path is compatible with all stages of manufacturing, it is selected as the best customer satisfying sustainable path for manufacturing the edible oil container.

4.4 RESULTS AND DISCUSSION

The implementation of CSRE Matrix for developing a 500 ml container for edible oil was carried out in a bottle manufacturing company. The path matrices for three stages of PDC for the new product development namely, MS, MPS and DS were developed. The most sustainable combination path for the development of the 500 ml container was identified.

A feedback session was conducted in the company for assessing the effectiveness of CSRE Matrix. A questionnaire was prepared to get the feedback. Design team and the panel of experts have participated in this feedback session. Five questions were asked to the seven experts who have participated in the implementation study. The respondents were asked to give their opinion on a likert scale of 1 to 9, where a response of 1 indicate the disagreement and 9 indicate complete agreement. The average score obtained for all the five questions is 7.11, with a maximum range of 2. This indicated that the respondents agree that the proposed CSRE Matrix can be used as a tool for customer satisfying sustainable product development. The summary of the feedback is shown in Table 4.11.

4.4.1 Statistical analysis

One sample ‘t’ test has been conducted to assess the acceptance of the feedback of CSRE Matrix. In the initial case the test value was given as 8.1, which means the null hypothesis was set as “90% of the opinion of the experts support the implementation of CSRE Matrix in the firm with the inclusion of all relevant CRs and all factors of sustainability under the sustainable development at 95% confidence level”. Null hypothesis was rejected in this case.

In the next case, test value was set at 7.2 which mean the null hypothesis was set at as “80% of the opinion of the experts support the implementation of CSRE Matrix in the firm with the inclusion of all relevant factors of sustainability under the sustainable development at 95% confidence level”. Null hypothesis was supported this case with ‘p’ values greater than 0.05. The details of the ‘t’ test are shown in Table 4.12. In short, the experts who have been surveyed feels that the CSRE Matrix can be implemented with 80 percent acceptance.

Table 4.10
Distribution Selection Matrix

Distribution Selection Matrix													
Material Options	Processes Options	Distribution Options	CRs	HDR	HTR	LPAC	LDC	Total CR Score	SRs	LPW	Total SR Score	Previous Path Score	CSRE Score
			Weight	0.05	0.01	0.14	0.11		Weight	0.04			
			BPW	0.50					BPW	0.50			
HDPE	Injection molding	EBP	Rating to EBP	6	6	8	9	0.67	Rating to EBP	2.00	0.04	6.41	7.12
			Score	0.14	0.03	0.57	0.49		Score	0.04			
		SSP	Rating to SSP	9	10	2	3	0.43	Rating to SSP	7	0.14	6.41	6.98
			Score	0.22	0.05	0.14	0.16		Score	0.14			
	Extrusion Blow Molding	EBP	Rating	6	6	8	9	0.67	Rating	2	0.04	6.43	7.14
			Score	0.14	0.03	0.57	0.49		Score	0.04			
		SSP	Rating to SSP	9	10	2	3	0.43	Rating to SSP	7	0.14	6.43	7.00
			Score	0.22	0.05	0.14	0.16		Score	0.14			
PET	Injection molding	EBP	Rating	6	6	8	9	0.67	Rating	3	0.06	4.79	5.51
			Score	0.14	0.03	0.57	0.49		Score	0.06			
		SSP	Rating to SSP	9	10	2	3	0.43	Rating to SSP	7	0.14	4,79	5.36
			Score	0.22	0.05	0.14	0.16		Score	0.14			
	Injection molding & Stretch blow molding	EBP	Rating	6	6	8	9	0.67	Rating	3	0.06	4.86	5.51
			Score	0.14	0.03	0.57	0.49		Score	0.06			
		SSP	Rating to SSP	9	10	2	3	0.43	Rating to SSP	7	0.14	4.86	5.36
			Score	0.22	0.05	0.14	0.16		Score	0.14			
	Extrusion Blow Molding	EBP	Rating	6	6	8	9	0.67	Rating	2	0.04	4.53	5.24
			Score	0.14	0.03	0.57	0.49		Score	0.04			
		SSP	Rating to SSP	9	10	2	3	0.43	Rating to SSP	7	0.14	4.53	5.10
			Score	0.22	0.05	0.14	0.16		Score	0.14			

Table 4.11
Expert's feedback on CSRE Matrix

Sr. No.	Question	Responses of experts							Average	Range
		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7		
1	The proposed tool can be used as an important tool for the development of a sustainable product in your organization. To what degree you support this statement?	8	7	8	8	7	7	8	7.57	2
2	The proposed tool has considered all the relevant customer requirements and asses the technical descriptors based on these requirements. To what degree you support this statement?	7	8	7	7	7	8	7	7.29	1
3	The proposed tool has considered all the relevant sustainability requirements under the pillar economy and asses the technical descriptors based on these requirements. To what degree you support this statement?	7	7	6	7	6	7	8	6.86	2
4	The proposed tool has considered all the relevant sustainability requirements under the pillar environment and asses the technical descriptors based on these requirements. To what degree you support this statement?	7	5	7	6	7	8	7	6.71	2
5	The proposed tool has considered all the relevant sustainability requirements under the pillar society and asses the technical descriptors based on these requirements. To what degree you support this statement?	7	8	6	7	6	8	8	7.14	2

Table 4.12
Details of 't' Test

Variables	Observations	Mean	Std. Deviation	Std. Error Mean	95% CI range	t value	p Value
1	7	7.57	0.54	0.20	(-0.12, 0.87)	1.84	0.12
2	7	7.29	0.49	0.18	(-0.37, 0.54)	0.47	0.66
3	7	6.86	0.69	0.26	(-0.98, 0.30)	-1.32	0.26
4	7	6.71	0.95	0.36	(-1.37, 0.40)	-1.35	0.23
5	7	7.14	0.90	0.34	(-0.89, 0.78)	-0.17	0.87

4.5 CHAPTER SUMMARY

The consideration of environmental requirements along with customer requirements in product development has gained significance during the last two decades (Vinod and Rathod, 2010). Even though, additional cost is incurred on the introduction of environmental requirements into new product development (kaebernick et al., 2002), manufacturing of environment friendly products is the need of the present era. In addition to environmental requirements, sustainability improvement efforts should satisfy economic and societal requirements at all levels viz. product, process and systems levels to make manufacturing systems more sustainable (Jayal et al., 2010). The manufacturing of customer oriented products at low cost is the backbone of the success of a manufacturing firm (Zhai et al., 2010).

Subjective methods such as ROC method and Analytic Hierarchy Process (AHP) are used to determine the weights among alternatives and are purely based on preferential judgments of decision maker. And also, there is no agreement among researchers that as to which method generate more accurate result (Ahn, 2011). ROC method is used as an efficient preliminary assessing method for determining the more promising alternatives which have to be studied in detail.

CSRE Matrix developed and test implemented in this doctoral work considers CRs and SRs separately and weigh their importance using ROC weights method. Subsequently, alternatives at each PDC were evaluated for developing a customer satisfying sustainable product. Different combinations of materials, processes and distribution methods were studied which helped in finding various possibilities for developing a customer satisfying sustainable product. The implementation study conducted has successfully illustrated the effectiveness of the proposed tool.

CHAPTER 5

CSRE MATRIX WITH AHP METHOD AND ITS IMPLEMENTATION STUDY

5. 1 PREAMBLE

Different weighing methods can be used in CSRE Matrix for arriving at importance weights of CRs and SRs. Analytic Hierarchy Process (AHP) is one of the methods that can be applied in CSRE Matrix to find importance weights of CRs and SRs. AHP is a multi-criteria decision support method where subjective opinion is converted in to an objective nature for the purpose of evaluation (Hermann et al., 2006). The objective of developing CSRE Matrix with AHP method is to weigh CRs and SRs in a more accurate way than ROC Weight method. In this chapter, development of CSRE Matrix using AHP is explained. The test implementation of the CSRE Matrix with AHP is also described in the subsequent sections.

5.2 ANALYTIC HIERARCHY PROCESS (AHP) AND ITS APPLICATION IN CSRE MATRIX

The AHP is a multi-criteria decision making tool developed by Saaty, used to simplify complex problems (Saaty, 2008, Saaty, 1990). A hierarchical structure of decision criteria such as objectives, options, criteria and sub-criteria are formulated and pair-wise comparisons are carried out between the elements of each level of the hierarchical structure. These pair-wise comparisons are used to obtain the importance weights of the elements. A major drawback of AHP methodology is that it allows for non-consistent pair-wise comparisons. Some of these pair-wise comparisons may not be performed correctly which would result in a mismatch between these comparisons. A consistency check mechanism has been included in AHP to identify the mismatch between the pair-wise comparisons.

AHP method has been used in many NPD techniques. Hsiao (2002) developed a method for NPD by integrating AHP, QFD, Failure Mode and Effect Analysis and Design for Assembly. This method used AHP to determine the importance weight of customer requirements for various criteria. Armacost et al. (1994) applied concurrent engineering method to evaluate production of exterior structural wall panel; where, AHP method has been used for prioritizing customer requirements in QFD. Hanumaiah et al. (2006) proposed combined AHP-QFD approach for rapid tooling process in which, AHP has been used to find importance weight of tooling requirements. In combined AHP-QFD approach proposed by Bhattacharya et al. (2005) for robot selection, AHP was used for evaluating importance weight of each robot considering its customer requirements and technical requirements.

A hierarchical structure of the elements has to be constructed for the application of AHP. The first level of hierarchical structure contains only one element which is the goal. In the case of CSRE Matrix, the goal is ‘Customer Satisfying Sustainable Product’. CRs and SRs are the elements in the second level. Third level contains the sub-elements of CRs and SRs. The schematic representation of hierarchical structure is shown in Fig. 5.1.

In AHP method, preferences between alternatives are found out by pair-wise comparison. The objective of pair-wise comparison is to determine the relative importance of these alternatives based on a criterion. The outcome of the pair-wise comparison is expressed as the importance rating. For each expression of importance, based on the intensity of relationship, a numerical value between 1 to 9 is assigned. These importance values are selected based on importance scale introduced by Saaty (Saaty, 2008, Saaty, 1980). The importance rating values are the members of the set: {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9}. These values and the definitions of the relationships are depicted in Table 5.1.

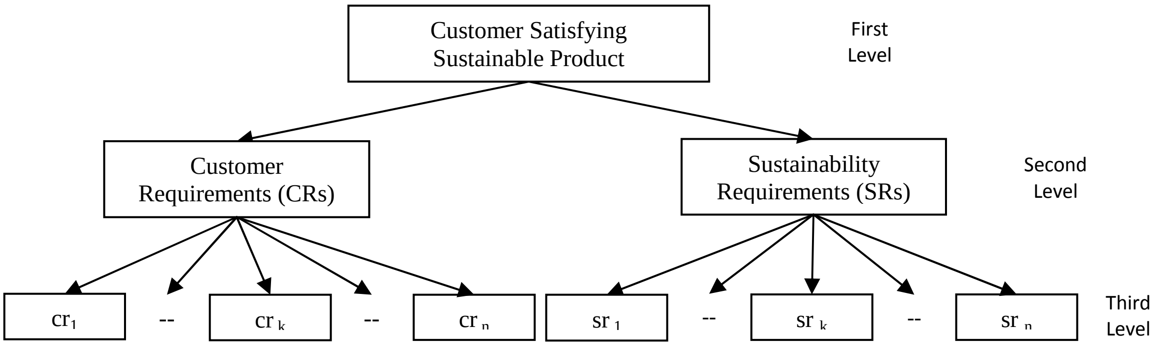


Figure 5.1 Hierarchical structure to carry out CSRE Matrix using AHP

The steps to be carried out in AHP are the following.

Step 1: Develop a pair-wise comparison matrix for the objective

Step 2: Add up the values in each column of the pair-wise comparison matrix

Step 3: Divide each value in each column of the pair-wise comparison matrix by the corresponding column sum. The resultant matrix is a normalized matrix.

Step 4: Calculate the average each value in each row of normalized matrix. The result gives the importance rating.

When the element is compared with itself, only one element exists in the level and the pair-wise comparison is of the order 1×1. For a 1×1 matrix, the importance weight assigned is 1. Second level consists of two elements as CR and SR. Pair-wise comparison is carried out between CR and SR to determine importance weight between them based on the criteria customer satisfying sustainable product. The resulting matrix is a 2×2 matrix. The importance weights assigned to them are termed as the business policy weights of CR and SR (BPWCR and BPWSR respectively) in the 'CSRE Matrix'. If CR has extreme importance over SR, a rating of 9 shall be given. If CR has equal importance to SR, a rating of 1 shall be given. The intermediate levels are chosen appropriately. The outcome of the pair-wise comparison is expressed as a matrix. This matrix is called judgment matrix.

According to Saaty (2008), the pair-wise comparisons in a judgment matrix are consistent if the corresponding consistency ratio (C_R) is less than 10%. The credibility of the judgement matrix and thereby importance weights calculated is determined by computing consistency index (C_I) and consistency ratio (C_R). C_I is calculated using the formula; $C_I = (\lambda max – n) / (n-1)$, where λmax is the principal eigen value of the judgement matrix and 'n' is the number of elements in the matrix.

Principal eigen value, λmax is obtained by adding, the results obtained by multiplying each sum value of column of pair-wise comparison matrix with the corresponding eigen vector value. Consistency ratio (C_R) is calculated by dividing C_I with random consistency index (RC_I) value, which is the average C_I of a randomly generated reciprocal matrix with dimension 'n' (Saaty, 1980; Asamoah et al., 2012). These RC_I values are shown in Table 5.2.

If 'n' is the number of elements considered in each row of pair-wise comparison matrix, then RC_I value is obtained from Table 5.2 corresponding to the 'n' value. If the calculated C_R value is less than 0.1, ie., 10%, the importance weight calculated is consistent; otherwise pair-wise comparison has to be revised until a C_R value of less than 0.1 is obtained (Ziout et al., 2013).

Table 5.1
Importance rating (Saaty, 2008)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favors one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favors one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity favored very strongly over another; its dominance demonstrated in practice.
8	Very , very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity I has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1 - 1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

In the case study considered, as there are only two elements in the second level, the consistency of pair-wise comparison matrix need not be checked (Saaty, 2008). The third level of hierarchy is the sub-elements of second level. Pair-wise comparison has been carried out to find the importance weights among CRs and SRs. The resulting importance weight obtained to each CR and SR are termed as the individual weight of CR and SR in the ‘CSRE Matrix’. For ‘n’ numbers of CRs, a judgment matrix of n×n order has to be constructed. Similarly, for ‘p’ numbers of SRs, a judgment matrix of p×p order has to be constructed.

Table 5.2
RCI values for different values of ‘n’

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Source: Triantaphyllou and Mann (1995)

5.3 CSRE MATRIX IMPLEMENTATION STUDY TO IMPROVE SUSTAINABILITY LEVEL OF 750 ML. BOTTLE

An implementation study has been carried out in a bottle manufacturing firm, M/s. Duropack Industries, located in Kerala state, India. The top management of the organization has provided their support to carry out the implementation study of CSRE Matrix. The product selected in this case study was 750 ml. container bottle which is used for filling Ayurvedic medicines. The implementation study of CSRE Matrix is explained in the succeeding paragraphs.

5.3.1 CSRE Matrix Phase-1

The design team comprising of Design Engineer, Quality Control Engineer and Safety Engineer were constituted by the top management to assist in implementation study. The development of CSRE Matrix in implementation study is explained in the following sections.

Step 1: Identify product, components of the product and PDC stages

The product identified for the implementation study was 750 ml. bottle. The components of the 750 ml. bottle were the bottle and its cap. Both the components are made up of the same material and considered as a single object to perform CSRE Matrix. The customers of 750 ml. bottles were Ayurvedic medicine manufacturers. Design team also selected the stages of PDC to carry out the CSRE Matrix. The stages considered were Materials Selection (MS), Manufacturing Process Selection (MPS) and Distribution Selection (DrS).

Step 2- Identify CRs

The design team constituted for the implementation study identified various CRs of 750 ml. bottle. For obtaining relevant CRs, design team discussed with the manufacturers of Ayurvedic medicine and also referred history of customer enquiries, company standards and market survey. CRs identified were minimum material cost, resilience to high impact load, excellent barrier to ultraviolet rays, excellent surface finish, minimum production cost, uniform wall thickness, high temperature resistance, minimum packing cost and minimum distribution cost. The CRs identified were subsequently segregated into the requirements of each stage of PDC. Table 5.3 shows various CRs and their segregation under different stages of product development.

Table 5.3
Customer Requirements

Sr. No.	CRs	Abbreviation	Product development Stage
1	Minimum Material Cost	MMC	Material Selection
2	Resilience to High Impact Load	IL	
3	Excellent Barrier to UV rays	EB	
4	Excellent Surface Finish	ESF	Manufacturing Process Selection
5	Minimum Production Cost	MPC	
6	Uniform Wall Thickness	UWT	
7	High Temperature Resistance	TR	Distribution Selection
8	Minimum Packing Cost	MPAC	
9	Minimum Distribution Cost	MDC	

Step 3 – Convert CRs to engineering requirements.

Design Team analyzed various CRs and reached to a consensus on suitable engineering requirements and options in MS, MPS, DrS stages of PDC. High Density Poly Ethylene and Poly Ethylene Terephthalate were the two options considered under MS stage. Injection moulding, extrusion blow moulding and stretch blow moulding were the three options considered for MPS stage. Standardized special packing (SSP) and economic bag packing (EBP) were the two options considered under DrS stage. Table 5.4 shows various options and CRs identified for different PDC stages.

Step 4: Identify SRs for each PDC.

CRs and engineering requirements were further analyzed by the design team. Brainstorming technique was applied among design team members to identify relevant SRs. Quality control engineer and safety engineer were able to provide key information in this regard. The stages of PDC, where the identified SRs can be fulfilled were also selected. Table 5.5 shows the various SRs identified and the stages of product development where it can be fulfilled.

Table 5.4
PDC Stages, Options and Customer Requirements

Stages	Options	CRs
Material Selection	HDPE	Minimum Material Cost, High Impact Load, Excellent Barrier
	PET	
Manufacturing Process Selection	Injection Moulding	Excellent Surface Finish, Minimum Production Cost, Unvarying Wall Thickness
	Injection Moulding and stretch blow moulding	
	Extrusion Blow Moulding	
Distribution Selection	Economic Bag Packing (EBP)	High Temperature Resistance, Minimum Packing Cost, Minimum Distribution Cost
	Standard Special Packing (SSP)	

Table 5.5
Sustainability Requirements

Sr. No.	Description	Abbreviation	Product development Stage
1	Recyclability	RC	Material Selection
2	Eco friendly Packing	EFP	Distribution Selection
3	Minimum Production Waste	MPW	Manufacturing Process Selection
4	Minimum content of additives	MCA	Material Selection
5	Less breakdown when exposed to ultra violet	LBU	Material Selection
6	Minimum Packing Waste	MPAW	Distribution Selection

Step 5: Ranking of CRs

The CRs identified were ranked based on their importance in each stage of PDC. The most important CR was given the rank one. The next important CR was ranked two and the ranking continued till all the CRs were ranked. Table 5.6 shows the ranking of each CR.

Step 6: Ranking of SRs

SRs under all stages of PDC were ranked subsequently. Similar to CRs these rankings were also carried out based on the importance of SRs in each stage of the PDC. The most important SR was ranked one. The next important SR was ranked two and ranking continued till all the SRs were ranked. Table 5.7 shows various SRs and their ranks

Table 5.6
Ranks of Customer Requirements

Sr. No.	CRs	Abbreviation	Rank
1	Minimum Material Cost	MMC	1
2	High Impact Load	IL	5
3	Excellent Barrier to UV rays	EB	6
4	Excellent Surface Finish	ESF	8
5	Minimum Production Cost	MPC	2
6	Unvarying Wall Thickness	UWT	9
7	Temperature Resistance	TR	7
8	Minimum Packing Cost	MPAC	3
9	Minimum Distribution Cost	MDC	4

Step 7: Assign weights to CRs

Ranking obtained for each CRs were then converted into weights. AHP method has been used for weighing CRs. The pair-wise comparison matrix and the weights assigned to each CR using AHP method is depicted in Table 5.8. The consistency ratio was also found out. The value obtained was 0.08, which being less than 0.1, the credibility of the pair-wise comparison was also established.

Table 5 .7
Ranks of Sustainability Requirements

Sr. No.	Description	Abbreviation	Ranks
1	Recyclability	RC	1
2	Eco friendly Packing	EFP	2
3	Minimum Production Waste	MPW	3
4	Minimum content of additives	MCA	4
5	Less breakdown to UV rays	LBU	5
6	Minimum Packing Waste	MPAW	6

Step 8: Assign weights to sustainability requirements

Similar to the weighing of CRs, AHP method was used to weigh different SRs. The pair-wise comparison matrix and the weights obtained for individual SRs are depicted in Table 5.9. As the consistency ratio obtained was 0.03, which is less than 0.1, the pair-wise comparison could be treated as credible and valid.

Table 5.8
Pair-wise comparison matrix of CRs and importance weights of CRs

CRs	MMC	MPC	MPAC	MDC	IL	EB	TR	ESF	UWT	Importance Weights
MMC	1	2	3	3	4	5	5	6	6	0.27
MPC	½	1	2	3	4	5	5	6	6	0.22
MPAC	1/3	1/2	1	1	3	4	4	5	6	0.15
MDC	1/3	1/3	1	1	2	3	4	4	5	0.12
IL	¼	1/4	1/3	1/2	1	3	4	5	6	0.09
EB	1/5	1/5	1/4	1/3	1/3	1	2	3	4	0.05
TR	1/5	1/5	1/4	1/4	1/4	1/2	1	3	3	0.04
ESF	1/6	1/6	1/5	1/4	1/5	1/3	1/3	1	3	0.03
UWT	1/6	1/6	1/6	1/5	1/6	1/4	1/3	1/3	1	0.02
C_I	0.08									
C_R	0.06									

Table 5.9
Pair-wise comparison matrix of SRs and importance weights of SRs

SRs	RC	EFP	MPW	MCA	LBU	MPAW	Importance Weights
RC	1	3	4	4	5	6	0.43
EFP	1/3	1	2	2	3	4	0.20
MPW	1/4	1/2	1	2	3	3	0.15
MCA	1/4	1/2	1/2	1	2	3	0.11
LBU	1/5	1/3	1/3	1/2	1	2	0.07
MPAW	1/6	1/4	1/3	1/3	1/2	1	0.05
C_I	0.04						
C_R	0.03						

Step 9: Assigning Business Policy Weights to CRs and SRs

While carrying out AHP for calculating BPWCR and BPWSR, the design team considered SRs as slightly important as compared to CRs. The pair-wise comparison matrix for CRs and SRs with their importance weight is given in Table 5.10.

Table 5.10
Pair-wise comparison matrix and importance weight of CRs and SRs

Customer Satisfying Sustainable Product	CRs	SRs	Importance Weights
CRs	1	2	0.67
SRs	½	1	0.33

5.3.2 CSRE Matrix Phase - 2

Phase-2 of CSRE Matrix includes steps to construct CSRE Matrices. The first CSRE Matrix constructed was MS Matrix. In MS Matrix, the alternative materials considered were High Density Poly Ethylene (HDPE) and Poly Ethylene Terephthalate (PET). HDPE and PET were the two paths in the CSRE matrix of the MS stage. ‘Minimum Material Cost (MMC)’, ‘High Impact Load (IL)’ and ‘Excellent Barrier to UV rays (EB)’ were the CRs identified in this stage.

The importance weights calculated for these CRs were 0.27, 0.09 and 0.05 respectively. ‘More Recyclability (RC)’, ‘Less breakdown when exposed to ultraviolet rays (LBU)’ and ‘Minimum Content of Additives (MCA)’ were the SRs identified in the MS stage. The importance weights calculated for these SRs were 0.43, 0.07 and 0.11 respectively. The ratings of alternative options were also carried out by the design team. The CSRE Matrix for the MPS and DrS stages of PDC were also developed by the design team.

The CSRE Matrix developed for MS, MPS and DrS stages are shown in Table 5.11, 5.12 and 5.13 respectively. CSRE Matrix for the DrS stage was the final matrix developed.

The path, which has the maximum score in the final matrix (DrS Matrix) was selected as the best path for producing the customer satisfying sustainable product.

Table 5.11
CSRE Matrix for Material Selection Stage

<table>
<tr><td colspan="13">Material Selection Matrix</td></tr>
<tr><td rowspan="3">Materials Options</td><td>CRs</td><td>MMC</td><td>IL</td><td>EB</td><td rowspan="3">Total CR Score</td><td>SRs</td><td>RC</td><td>MCA</td><td>LBU</td><td rowspan="3">Total SR Score</td><td rowspan="3">Previous Path Score</td><td rowspan="3">CSRE Score</td></tr>
<tr><td>CR Weight</td><td>0.27</td><td>0.09</td><td>0.05</td><td>SR Weight</td><td>0.43</td><td>0.11</td><td>0.07</td></tr>
<tr><td>BPWCR</td><td colspan="3">0.67</td><td>BPWSR</td><td colspan="3">0.33</td></tr>
<tr><td rowspan="2">HDPE</td><td>Rate to Option</td><td>6.00</td><td>6.00</td><td>8.00</td><td rowspan="2">1.74</td><td>Rate to Option</td><td>9.00</td><td>9.00</td><td>8.00</td><td rowspan="2">1.79</td><td rowspan="2">0</td><td rowspan="2">3.53</td></tr>
<tr><td>CR Score</td><td>1.09</td><td>0.37</td><td>0.28</td><td>CR Score</td><td>1.29</td><td>0.33</td><td>0.18</td></tr>
<tr><td rowspan="2">PET</td><td>Rate to Option</td><td>8.00</td><td>7.00</td><td>6.00</td><td rowspan="2">2.09</td><td>Rate to Option</td><td>6.00</td><td>2.00</td><td>4.00</td><td rowspan="2">1.02</td><td rowspan="2">0</td><td rowspan="2">3.11</td></tr>
<tr><td>CR Score</td><td>1.45</td><td>0.43</td><td>0.21</td><td>CR Score</td><td>0.86</td><td>0.07</td><td>0.09</td></tr>
</table>

The maximum CSRE Score obtained was 7.14. The options considered in that combination path were HDPE for MS stage, extrusion blow moulding for MPS stage and economic bag packing for DrS stage. This combination path was selected as the best sustainable and customer satisfying path for manufacturing 750 ml. container bottle for Ayurvedic medicine filling.

Table 5.12
CSRE Matrix for Manufacturing Process Selection Stage

Manufacturing Process Selection Matrix											
Materials Options	Processes Options	CRs	ESF	MPC	UWT	Total CR Score	SRs	MPW	Total SR Score	Previous Path Score	CSRE Score
		CR Weight	0.03	0.22	0.02		SR Weight	0.15			
		BPWCR	0.67				BPWSR	0.33			
HDPE	Injection molding	Rate to Option	9.00	6.00	9.00	1.18	Rate to Option	8.00	0.39	3.53	5.10
		CR Score	0.17	0.89	0.12		CR Score	0.39			
	Extrusion Blow Molding	Rate to Option	6.00	8.00	6.00	1.38	Rate to Option	6.00	0.29		5.21
		CR Score	0.11	1.19	0.08		CR Score	0.29			
PET	Injection molding	Rate to Option	9.00	6.00	9.00	1.18	Rate to Option	8.00	0.39	3.11	4.69
		CR Score	0.17	0.89	0.12		CR Score	0.39			
	Injection molding & Stretch Blow Molding	Rate to Option	8.00	7.00	8.00	1.30	Rate to Option	8.00	0.39		4.80
		CR Score	0.15	1.04	0.11		CR Score	0.39			
	Extrusion Blow Molding	Rate to Option	7.00	5.00	6.00	0.96	Rate to Option	6.00	0.29		4.36
		CR Score	0.13	0.74	0.08		CR Score	0.29			

Table 5.13
CSRE Matrix for Distribution Selection Stage

Distribution Selection Matrix													
Material Options	Processes Options	Distribution Methods Options	CRs	TR	MPAC	MDC	Total CR Score	SRs	EFP	MPW	Total SR Score	Previous Path Score	CSRE Score
			CR Weight	0.04	0.15	0.12		SR Weight	0.20	0.15			
			BPWCR	0.67				BPWSR	0.33				
HDPE	Injection molding	EBP	Rate to Option	3.0	8.00	9.0	1.60	Rate to Option	2.00	4.0	0.33	5.10	7.04
			CR Score	0.08	0.78	0.74		SR Score	0.135	0.20			
		SSP	Rate to Option	8.00	2.00	3.0	0.66	Rate to Option	8.00	6.00	0.83		6.60
			CR Score	0.22	0.20	0.25		SR Score	0.540	0.29			
	Extrusion Blow Molding	EBP	Rate to Option	3.00	8.00	9.0	1.60	Rate to Option	2.0	4.00	0.33	5.21	7.14
			CR Score	0.08	0.78	0.74		SR Score	0.14	0.20			
		SSP	Rate to Option	8.00	2.00	3.00	0.66	Rate to Option	8.00	6.00	0.83		6.70
			CR Score	0.22	0.20	0.25		SR Score	0.54	0.29			
PET	Injection molding	EBP	Rate to Option	3.00	8.00	9.00	1.60	Rate to Option	2.0	4.0	0.33	4.69	6.62
			CR Score	0.08	0.78	0.74		SR Score	0.14	0.20			
		SSP	Rate to Option	8.00	2.00	3.00	0.66	Rate to Option	8.00	6.00	0.83		6.18
			CR Score	0.22	0.20	0.25		SR Score	0.54	0.29			
	Injection molding & Stretch blow molding	EBP	Rate to Option	3.00	8.00	9.00	1.60	Rate to Option	2.00	4.00	0.33	4.80	6.74
			CR Score	0.08	0.78	0.74		SR Score	0.14	0.20			
		SSP	Rate to Option	8.00	2.00	3.00	0.66	Rate to Option	8.00	6.00	0.83		6.30
			CR Score	0.22	0.20	0.25		SR Score	0.54	0.29			
	Extrusion Blow Molding	EBP	Rate to Option	3.00	8.00	9.00	1.60	Rate to Option	2.00	4.00	0.33	4.36	6.30
			CR Score	0.08	0.78	0.74		SR Score	0.14	0.20			
		SSP	Rate to Option	8.00	2.00	3.00	0.66	Rate to Option	8.00	6.00	0.83		5.86
			CR Score	0.22	0.20	0.25		SR Score	0.54	0.29			

5.4 RESULTS AND DISCUSSION

The CSRE Matrix was used to analyze the alternative options for developing the 750 ml. container bottle for filling Ayurvedic medicine. The path matrices for MS, MPS and DrS were developed accordingly. The options that are most suitable for the development of the 750 ml. container were identified for each stage of the PDC.

The assessment of the effectiveness of the CSRE Matrix was also carried out by collecting the feedback from a panel of experts in the company. The panel of experts comprised of Quality Control Manager, Production Manager, Sales Manager, Logistics Manager and the design team members. Three questions were asked to the seven experts who have participated in the implementation study. The respondents were asked to give their opinion on a likert scale of 1 to 9, where a response of 1 indicate the disagreement and 9 indicate complete agreement. The questions asked and the responses of the experts are shown in Table 5.14. The average score obtained for all the three questions put together is 6.48, with a maximum range of 2. The summary of the feedback is shown in Table 5.14. The feedback result indicates that the proposed CSRE Matrix can be used as a tool for customer satisfying sustainable product development.

5.4.1 Statistical Analysis

In order to assess the acceptance of the feedback of CSRE Matrix, one sample ‘t’ test was conducted. In the initial case the test value was taken as 7.2, which means the null hypothesis is as “80% of the opinion of the experts supports the implementation of SPM tool in the firm and all relevant CRs and SRs have been considered at 95% confidence level”. Null hypothesis was rejected in this case.

Table 5.14
Expert's feedback on CSRE Matrix

Sr. No.	Question	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Average	Range
1	To what degree you support that CSRE Matrix can be used as a tool for the development of a sustainable and customer satisfying product in your organization?	6	7	6	7	5	7	7	6.43	2
2	To what degree you support that CSRE Matrix is assessing alternative options based on the relevant customer requirements considered?	6	6	7	7	7	6	7	6.57	1
3	To what degree you support that CSRE Matrix is assessing alternative options based on relevant sustainability requirements considered?	6	7	7	7	6	7	5	6.43	2

When test value was set at 6.75 which modifies the null hypothesis as "75% of the opinion of the experts support the implementation of CSRE Matrix in the firm and all relevant CRs and SRs have been considered at 95% confidence level". Null hypothesis was supported this case with all 'p' values greater than 0.05. Table 5.15, shows the details of 't' test. The experts who have been surveyed agree that the CSRE Matrix can be implemented with 75 percent acceptance.

Table 5.15
Details of ‘t' Test

Variables	Observations	Mean	Std. Deviation	Std. Error Mean	95% CI range	‘t’ value	‘p’ Value
1	7	6.43	0.79	0.30	(-1.05, 0.41)	-1.08	0.32
2	7	6.57	O.54	0.20	(-0.67, 0.32)	-0.88	0.41
3	7	6.43	0.79	0.30	(-1.05, 0.41)	-1.08	0.32

5.5 CHAPTER SUMMARY

Developing tools that help to fulfill CRs and SRs in NPD is a difficult mission. The development of CSRE Matrix with AHP method presented in this chapter is a step towards achieving these objectives. This tool helps the designers to consider both the CRs and SRs while design and development of the products.

In CSRE Matrix with AHP method, Brainstorming technique has been used to unearth various CRs and SRs. Further, to weigh CRs and SRs, AHP method was adopted in this tool. The case study conducted for the test implementation and the feedback from the practitioners proved its usefulness and importance in NPD.

CHAPTER 6

CSRE MATRIX WITH FUZZY ANALYTIC HIERARCHY PROCESS AND ITS IMPLEMENTATION STUDY

6.1 PREAMBLE

The success of a product in the market depends on its ability to satisfy its customers (Ali et al., 2012). Customers' satisfaction depends on the extent to which the product can satisfy their requirements. These requirements may be contradicting and the cost associated with fulfilling them can also be different. Customer requirements have to be assessed and the priority of these requirements need to be fixed before incorporating them into a new product (Alemam and Li, 2014). Weighing of customer requirements according to their varying importance levels is one of the important steps in New Product Development (NPD).

The requirements of customers would be subjective in nature. Researchers have attempted various methods to convert subjective nature of an opinion to objective evaluation. One of such method is Fuzzy Analytic Hierarchy Process (FAHP). In this chapter, application of FAHP method in CSRE Matrix to weigh the importance levels of Customer Requirements (CRs) and Sustainability Requirements (SRs) is explained. An implementation study of CSRE Matrix in an umbrella manufacturing industry is also included.

6.2 FUZZY ANALYTIC HIERARCHY PROCESS

Fuzzy Analytic Hierarchy Process (FAHP) is an extended version of Analytic Hierarchy Process (AHP) method. In AHP, pair-wise comparisons are carried out between objectives, options, criteria etc. by judgments of experts (Sadiq et al., 2005). This method is used in several research works for determining relative importance of variables (Kwong and Bai, 2002). The 'importance scale' developed by Saaty (1980) is used to compare various options. The importance scale is having 9 levels depending on the intensity of the relationship between the factors.

In most of the cases, these levels developed by Saaty (1980) are not adequate to represent the linguistic variables due to complex nature of the subjective human decisions. Application of fuzzy logic is appropriate in such cases (Kwong and Bai, 2002; Bottani and Rizzi, 2006). Fuzzy set theory developed by Zadeh (1965) is used to solve judgment problems, which are subjective in nature. According to Ali et al. (2012), subjective nature of human decisions can be treated in a fuzzy environment and solved by 'fuzzy decision making approach'.

Fuzzy Analytic Hierarchy Process (FAHP) is a fuzzy decision making approach having many applications in the research arena (Ugurlu et al ., 2015). In 'CSRE Matrix' the importance of CRs, SRs and their sub-elements are assessed and weighed using FAHP procedure. There are many FAHP methods developed by researchers in literature (Ugurlu, 2015). One of the latest approaches on the FAHP methodology is 'Chang's extent analysis' method (Ghadimi et al., 2012; Celik et al., 2009; Ugurlu, 2015).

6.2.1 Chang’s extent FAHP procedure

Chang’s extent analysis method is relatively easier while comparing with other approaches of FAHP (Ghadimi et al., 2012). The procedure of carrying out ‘Chang’s extent analysis’ is as described under (Ghadimi et al., 2012; Kahraman et al., 2004):

Let X = $\{x_1, x_2, \ldots\ldots x_m\}$ be an object set against a goal. Object set includes various objectives. In the development of CSRE Matrix, various customer requirements and sustainability requirements constitute two object set. In Changs’ extent analysis method, these objectives are compared with one another based on their importance level against that goal. For this, pair-wise comparison is carried out between these objectives within an object set. To compare the objectives against a goal, fuzzy AHP linguistic scale as shown in Table 6.1 is used. Against each linguistic scale, a triangular fuzzy scale is developed as depicted in Table 6.1 (Ghadimi et al., 2012).

Table 6.1
Fuzzy AHP linguistic scale

Linguistic Scale	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Just Equal	(1,1,1)	(1,1,1)
Equally Important	(1,1,3)	(1/3,1,1)
Weakly Important	(1,3,5)	(1/5,1/3,1)
Essentially Important	(3,5,7)	(1/7,1/5,1/3)
Very Strongly Important	(5,7,9)	(1/9,1/7,1/5)
Absolutely Important	(7,9,9)	(1/9,1/9,1/7)

The selection of triangular fuzzy scale against a linguistic scale and the steps to be followed in Chang’s extent analysis are described below.

Step 1: The first step in fuzzy AHP extent analysis method is to carry out the pair-wise comparison that decides the relative importance of each objective.

Let, O^1_{gi}, O^2_{gi},....O^m_{gi} are trianglar fuzzy numbers that can be displayed as (a,b,c). In the CSRE Matrix, these triangular fuzzy numbers are triangular fuzzy scales obtained after comparing one objective with other ‘m’ number of objectives against the i^{th} goal.

Where,

i = 1,2,------, n number of goals.

A Fuzzy evaluation matrix is developed using these triangular fuzzy scales. Table 6.9 is an example of evaluation matrix. For each objective after comparing with other objectives a ‘fuzzy synthetic extent value’, ‘P_i’ is calculated using Eq. 6.1.

P_i of an objective is obtained using the following equation.

$P_i = \sum_{j=1}^{m} O^j_{gi} \times [\sum_{i=1}^{n} \sum_{j=1}^{m} O^j_{gi}]^{-1}$…………… (Eq. 6.1)

Where,

j = 1, 2, 3, ------, m number of objectives.

Fuzzy addition operation $\sum_{j=i}^{m} O^j_{gi}$ is carried out as shown below;

$\sum_{j=1}^{m} O^j_{gi} = (a_{i1}, b_{i1}, c_{i1}) + (a_{i2}, b_{i2}, c_{i2}) + ... + (a_{im}, b_{im}, c_{im})$

$= (\sum_{j=1}^{m} aij ; \sum_{j=1}^{m} bij ; \sum_{j=1}^{m} cij)$

$= (a'_i, b'_i, c'_i)$ ……………………………… (Eq. 6.2)

$$[\sum_{i=1}^{n}\sum_{j=1}^{m} O^{j}{}_{gi}] = \sum_{i=1}^{n} [\sum_{j=1}^{m} aij, \sum_{j=1}^{m} bij \sum_{j=1}^{m} cij]$$

$$=[\sum_{i=1}^{n} a'i, \sum_{i=1}^{n} b'i, \sum_{i=1}^{n} c'i]$$

$$[\sum_{i=1}^{n}\sum_{j=1}^{m} O^{j}{}_{gi}]^{-1} = [\frac{1}{\sum_{i=1}^{n} c'i}, \frac{1}{\sum_{i=1}^{n} b'i}, \frac{1}{\sum_{i=1}^{n} a'i}]$$

$$= (a'_i, b'_i, c'_i) \times [\frac{1}{\sum_{i=1}^{n} c'i}, \frac{1}{\sum_{i=1}^{n} b'i}, \frac{1}{\sum_{i=1}^{n} a'i}]$$

$$\sum_{j=i}^{m} O^{j}{}_{gi} \times [\sum_{i=1}^{n}\sum_{j=1}^{m} O^{j}{}_{gi}]^{-1} = [\frac{a'i}{\sum_{i=1}^{n} c'i}, \frac{b'i}{\sum_{i=1}^{n} b'i}, \frac{c'i}{\sum_{i=1}^{n} a'i}]$$

$$= (a_i, b_i, c_i)$$

Fuzzy synthetic extent value obtained for each objective is compared with one another and find out the degree of possibility of each objective. In step 2, possibility degree calculations are explained. The normalized value of degree of possibility of each objective is considered as the weight of the objective.

Step 2: Possibility degree calculation

To find out the weight of each objective, possibility degree of each objective has to be calculated. This is carried out by comparing the fuzzy synthetic extent values of different objectives. The possibility degree between two triangular fuzzy numbers is depicted in Fig. 6.1. P_i and P_k are indicated using $P_i = (a_i, b_i, c_i)$ and $P_k = (a_k, b_k, c_k)$.

Let the possibility degree for $P_i \geq P_k$ is represented as $V (P_i \geq P_k)$.

$$V (P_i \geq P_k) = \text{Highest } (P_i \cap P_k) = \mu_{si}(d)$$

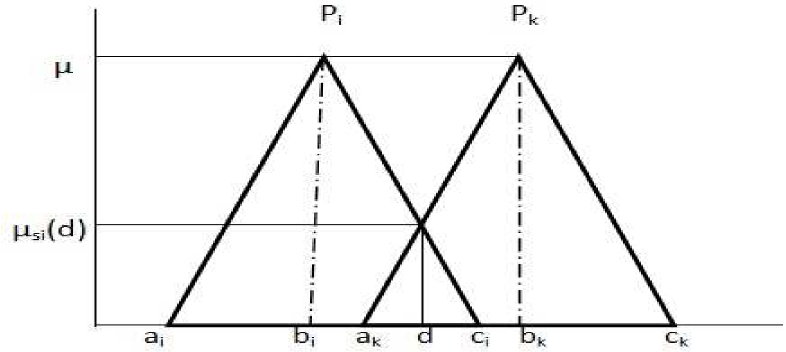


Figure 6.1 Possibility degrees between two triangular fuzzy numbers

$V(P_i \geq P_k) = \mu_{si}(d) =$ if $(a_i \geq a_k)$; 1

if $(a_k \geq c_i)$; 0

Otherwise, $\frac{ak-ci}{(bi-ci)-(bk-ak)}$

Where ‘d’ is the ordinate of the highest intersecting point between μ_{si} and μ_{sk}.

Step 3:

The degree of possibility for a fuzzy number to be greater than k fuzzy numbers P_i; where i = 1, 2... k is defined as;

$V(P \geq P_1, P_2 \ldots P_k) = (V(P \geq P_1), V(P \geq P_2) \ldots V(P \geq P_k)$

$= \text{Min}((V(P \geq P_1), V(P \geq P_2) \ldots V(P \geq P_k))$

$= \text{Min } V(P \geq P_i)$ where i =1, 2, 3...k.

If it is assumed that for (k=1, 2, 3……………...n, $k \neq i$), $d'(A_i) = \text{Min}(P_i \geq P_k)$ then weight vector is given by

$W' = (d'(A_1), d'(A_2) \ldots d'(A_n))^T$

Where A_i = (1, 2,.....n) are ‘n’ elements.

Step 4:

By normalizing the weight vector, the ‘importance weight’ of individual objective is obtained as prescribed below

$W = (d(A_1), d(A_2)....d(A_n))^T$, where ‘W’ is a real number.

6.3 IMPLEMENTATION OF ‘CSRE MATRIX’ IN AN UMBRELLA MANUFACTURING INDUSTRY

An implementation study of the CSRE Matrix with FAHP was conducted in an organization to verify its effectiveness. As mentioned earlier, this case study was conducted in an umbrella manufacturing company (hereafter referred as UMC). UMC is located in Alappuzha district in Kerala State, India. Upon contacting, the top management of the company was keen on conducting the case study in their organization as this effort would make UMC an environment friendly manufacturing company.

The product selected for the case study was ‘walking stick umbrella’. Executives of UMC unanimously selected this product, as it had maximum demand during the last financial year. A design team was constituted to design a new sustainable customer satisfying ‘walking stick umbrella’. The members of the team were Production Engineer, Design Engineer, Sales Manager and Safety Engineer.

6.3.1 CSRE Matrix implementation and data collection – CSRE Phase-1

CSRE Matrix is constructed in two phases. Phase -1 included the nine steps explained in section 3.3. Implementation of these steps for the development of the component ‘umbrella cloth’ of the product ‘walking stick umbrella’ is explained in subsequent sections.

Step 1 – Identify components of product and PDC stages

Selection of product, identifying its components and PDC stages were carried out primarily. The major components of walking stick umbrella are shown in Table 6.2. The design team unanimously agreed on PDC stages as ‘Design Selection’ (DS), ‘Material Selection’ (MS), ‘Manufacturing Process Selection’ (MPS), Usage Selection (US), Disposal Selection (DiS) and ‘Distribution Selection’ (DrS).

Step 2 - Identify CRs

Design team collected various CRs (Sub-elements of CRs) of umbrella cloth by applying brain storming techniques. The sales manager provided key information in this regard. These requirements were subsequently allocated to each stage of PDC, according to the stage where it can be fulfilled.

Step 3 - Convert CRs to engineering requirements

After analyzing CRs at each stage of PDC, design team identified engineering requirements of DS, MS, MPS, US and DiS stages of PDC for producing the components of the product. These engineering requirements were converted as options under different stages of PDC. CRs and options of each stage of the component ‘Umbrella Cloth’ are shown in Table 6.3. The DrS stage of PDC is relevant for the final product manufactured by assembling the components. The options of DrS and the CRs are shown in Table 6.4.

The CSRE Matrix of DrS has also constructed to compare the path of developing a sustainable final product.

Table 6.2
Major components of an Umbrella

Component Number	Description of Components
1	Umbrella cloth
2	Crook Handle
3	Tube/Shaft
4	Tube Runner
5	Skelton (Ribs and Stretcher)

Step 4 – Identify SRs

Design team identified various SRs of umbrella cloth also by applying brain storming techniques. SRs identified and its segregation into each stage of PDC is shown in Table 6.5. The options of DrS stage with their SRs are shown in Table 6.6.

Table 6.3
PDC stages, Options and CRs of the component 'Umbrella Cloth'

Stages	Options	CRs
Design	Circular cloth	Better Appearance (BA), More Area Coverage (MAC)
	Circular shaped cloth with added frill	
Material	Nylon Taffeta	Reduced Material Cost (RMTC), More Wrinkle Free (MRF), More Water Repellent (MWR)
	Pongee Fabric	
	Cotton Fabric	
	Poly Propylene	
Manufacturing	Nylon production (NP) and Stitching	Reduced Manufacturing Cost (RMNC)
	Pongee Production (PP) and stitching	
	Cotton Production(CP) and Stitching	
	Poly propylene Production (PPP) and Stitching	
Usage	All Seasons	More Overall Rigidity (MOR)
Disposal	Recycle	More Resale Value (MRV)
	Dispose	

Table 6.4
PDC stage, Options and CRs of Distribution Selection

Stage	Options	CRs
Distribution	Plastic Bags	Reduced Packing Cost (RPC)
	Plastic Wrapping	

Table 6.5

PDC stages, Options and SRs of the component 'Umbrella Cloth'

PDC stages	Options	SRs
Design	Circular cloth	More Heat Dissipation (MHD)
	Circular shaped cloth with added frill	
Material	Nylon Taffeta	Less Harmful to Environment (LHE)
	Pongee Fabric	
	Cotton Fabric	
	Poly Propylene	
Manufacturing	Nylon production (NP) and Stitching	More Worker Safety (MWS), Reduced Wastage (RW)
	Pongee Production (PP) and stitching	
	Cotton Production(CP) and Stitching	
	Poly propylene Production (PPP) and Stitching	
Usage	All Seasons	More Durable (MD)
Disposal	Recycle	Easily Degradable (ED), More Recyclable (MR)
	Dispose	

Table 6.6
PDC stage, Options and SRs of Distribution Selection

Stage	Options	SRs
Distribution	Plastic Bags	More Recyclable (MR), Easily Degradable (ED)
	Plastic Wrapping	

Step 5 - Ranking of CRs

CRs identified are ranked based on their importance in each stage of PDC. For this, CRs identified in the entire stages of PDC are considered together and ranked by design team. CRs and their ranking are given in Table 6.7.

Table 6.7
CRs and their importance ranking for the ‘Umbrella Cloth’

CRs	Abbreviation	Ranks
Better Appearance	BA	6
More Area Coverage	MAC	5
Reduced Material Cost	RMTC	2
More Wrinkle Free	MRF	4
More Water Repellent	MWR	3
Reduced Manufacturing Cost	RMNC	1
More Overall Rigidity	MOR	7
More Resale Value	MRV	8

Step 6 - Ranking of SRs

SRs identified were ranked based on their importance in each stage of PDC. For this, SRs identified in the entire stages of PDC were grouped together and ranked by design team. SRs and their ranking are given in Table 6.8.

Table 6.8
SRs and their importance ranking for the ‘Umbrella Cloth’

SRs	Abbreviation	Ranks
More Heat Dissipation	MHD	6
Less Harmful to Environment	LHE	1
More Worker Safety	MWS	7
Reduced Wastage	RW	5
More Durable	MD	4
Easily Degradable	ED	3
More Recyclable	MR	2

Step 7 - Assign weights to CRs

The ranking obtained for each CRs have to be converted into weights. The weighting method used is Fuzzy Analytic Hierarchy Process (FAHP) as explained in section 6.2. Fuzzy pair-wise comparison matrices of sub-elements of CRs for Umbrella Cloths are shown in Tables 6.9. Table 6.10 shows the weights of various CRs obtained for component Umbrella Cloth by carrying out Chang’s FAHP Procedure. Table 6.11 shows the weight assigned to the CRs at DrS stage. The fuzzy pair-wise comparison matrix of CRs at DrS stage is a matrix of 1×1 order and hence the weight is given as 1.

Table 6.9
Fuzzy Pair wise comparison matrix for elements of CRs of ‘Umbrella Cloth’

CRs	RMTC	RMNC	MWR	MRF	MAC	BA	MOR	MRV
RMTC	(1,1,1)	(1,1,3)	(1,1,3)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(5,7,9)
RMNC	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)	(5,7,9)
MWR	(1/3,1,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)
MRF	(1/3,1,1)	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)
MAC	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)	(3,5,7)
BA	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)
MOR	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)	(1,3,5)
MRV	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)

Table 6.10
Weights of various CRs of 'Umbrella Cloth'

Weights of CRs – Umbrella Cloth							
Reduced Material Cost (RMTC)	Reduced Manufacturing Cost (RMNC)	More Water Repellent (MWR)	More Wrinkle Free (MRF)	More Area Coverage (MAC)	Better Appearance (BA)	More Overall Rigidity (MOR)	More Resale Value (MRV)
0.188	0.20	0.16	0.15	0.13	0.08	0.06	0.03

Table 6.11
Weights of CRs of DrS stage

Weights of CRs – DrS stage
Reduced Packing Cost (RPC)
1

Step 8 - Assign weights to sustainability requirements

Similar to the weighing of CRs, weighting of SRs were also carried out by Fuzzy Analytic Hierarchy Process (FAHP) procedure. Fuzzy pair-wise comparison matrices of sub-elements of SRs for Umbrella Cloths are shown in Table 6.12. Table 6.13 shows the weights of various SRs obtained for component Umbrella Cloth. Fuzzy Pair wise comparison matrix for elements of SRs of DrS stage is shown in Table 6.14. The weights obtained for sub elements of SRs at distribution selection is shown in Table 6.15

Table 6.12
Fuzzy Pair wise comparison matrix for elements of SRs of 'Umbrella Cloth'

SRs	LHE	MR	ED	MD	RW	MHD	MWS
LHE	(1,1,1)	(1,1,3)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)
MR	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)
ED	(1/3,1,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,1,3)	(1,3,5)	(3,5,7)
MD	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)	(1,3,5)
RW	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1/3,1,1)	(1,1,1)	(1,1,3)	(1,3,5)
MHD	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/3,1,1)	(1,1,1)	(1,3,5)
MWS	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)

Table 6.13
Weights of various SRs of 'Umbrella Cloth'

Weights of Sustainability Requirement – Umbrella Cloth						
Less Harmful to Environment (LHE)	More Recyclable (MR)	Easily Degradable (ED)	More Durable (MD)	Reduced Wastage (RW)	More Heat Dissipation (MHD)	More Worker Safety (WS)
0.21	0.21	0.19	0.15	0.12	0.10	0.03

Table 6.14
Fuzzy Pair wise comparison matrix for elements of SRs of DrS stage

Distribution	More Recyclability (RCY)	More Degradability
More Recyclability (RCY)	(1,1,1)	(1,1,3)
More Degradability	(1/3,1,1)	(1,1,1)

Table 6.15
Weights of SRs of DrS stage

Weights of SRs–DrS stage	
More Recyclable (MR)	More Degradable (MD)
0.50	0.50

Step 9 - Assign business policy weights to CR and SR

In an ideal business situation, CRs and SRs are given equal preferences. However, due to certain business constraints and competitions, organization may not be able to do the same. In such cases, weights for the CRs and SRs can be modified by the management. FAHP procedure explained in section 6.2 was also carried out to determine this business policy weights ‘BPWCR’ and ‘BPWSR’. The management has weighed CRs and SRs equally and the weights obtained are 0.5 each. Fuzzy pair wise comparison matrices for ‘BPWCR’, ‘BPWSR’ and the weights obtained are shown in Table 6.16 and 6.17 respectively.

Table 6.16
Fuzzy Pair wise comparison matrix for ‘Business Policy Weight’

Business Policy Weight	BPWCR	BPWSR
BPWCR	(1,1,1)	(1,1,3)
BPWSR	(1/3,1,1)	(1,1,1)

Table 6.17
Weights assigned to 'BPWCR' and 'BPWSR'

BPWCR	BPWSR
0.50	0.50

6.3.2 CSRE Matrix implementation and data collection – Phase- 2

The construction of CSRE Matrices in 6 steps as explained in section 6.2 was carried out in the second phase. The DS stage of CSRE Matrix of umbrella cloth was first developed which is shown in Table 6.18. 'Better Appearance' (BA) and 'More Area Coverage' (MAC) were the CRs considered. The weights obtained for 'BA' and 'MAC' were 0.08 and 0.13 respectively. 'More Heat Dissipation' (MHD) was the SR considered for DS matrix and the weight obtained was 0 .10.

The ratings of options based on their fulfillment level on CRs and SRs were carried out by the expert team. Each option is rated in Likert scale of 1 to 9. The option that fulfills CR or SR totally shall be given a rating of 9. The option that does not fulfill CR or SR shall be given a rating of 1. The intermediate ratings were given for partial fulfillment of CR and SR.

Table 6.18
DS Stage of CSRE Matrix

CSRE Matrix for Design Selection– Umbrella Cloth									
Design Options	CRs	BA	MAC	Total CR Score	SRs	MHD	Total SR Score	PPS	CSRE Score
	CR Weight	0.08	0.13		SR Weight	0.10			
	BPWCR	0.50	0.50		BPWSR	0.50			
Circular Cloth	Rating to Circular Cloth	5.00	3.00	0.39	Rating to Circular Cloth	4.00	0.19	0	0.58
	CR Score	0.19	0.20		SR Score	0.19			
Circular Cloth with frill	Rating to Circular Cloth with frill	4.00	6.00	0.55	Rating to Circular Cloth with frill	6.00	0.29	0	0.84
	CR Score	0.16	0.40		SR Score	0.29			

As explained in Chapter 3, Section 3.2.1.2, ‘CR Score’, ‘SR Score’ and ‘CSRE Score’ were calculated for each option. Umbrella cloth of circular shape design got a ‘SPM Score’ 0.59; whereas, umbrella cloth of circular shape with added frill obtained a score 0.84. ‘PPS’ was assigned zero, as it was the first matrix constructed.

MS, MPS, US, DiS and DrS stage CSRE Matrices were also developed for Umbrella Cloth. These matrices are presented in Tables 6.19, 6.20, 6.21, 6.22 and 6.23 respectively.

Table 6.19
MS Stage of CSRE Matrix

CSRE MATRIX FOR MATERIAL SELECTION - UMBRELLA CLOTH											
Design Options	Material Options	CRs	MWR	RMTC	MRF	Total CR Score	SRs	LHE	Total SR Score	PPS	CSRE Score
		CR Weight	0.16	0.19	0.15		SR Weight	0.21			
		BPWCR	0.50	0.50	0.50		BPWSR	0.50			
Circular Cloth	Nylon	Rate to Nylon	6.00	8.00	8.00	1.83	Rate to Nylon	3.00	0.31	0.58	2.73
		CR Score	0.47	0.75	0.61		SR Score	0.31			
	Pongee	Rate to Pongee	8.00	2.00	3.00	1.05	Rate to Pongee	4.00	0.42	0.58	2.05
		CR Score	0.63	0.19	0.23		SR Score	0.42			
	Cotton	Rate to Cotton	2.00	8.00	3.00	1.14	Rate to Cotton	8.00	0.83	0.58	2.55
		CR Score	0.16	0.75	0.23		SR Score	0.83			
	Poly Propylene	Rate to Poly Propylene	5.00	3.00	5.00	1.06	Rate to Poly Propylene	4.00	0.42	0.58	2.06
		CR Score	0.39	0.28	0.38		SR Score	0.417			
Circular Cloth with frill	Nylon	Rate to Nylon	6	8	8	1.83	Rate to Nylon	3.00	0.31	0.84	2.99
		CR Score	0.47	0.75	0.61		SR Score	0.31			
	Pongee	Rate to Pongee	8	2	3	1.05	Rate to Pongee	4.00	0.417	0.84	2.30
		CR Score	0.63	0.19	0.23		SR Score	0.42			
	Cotton	Rate to Cotton	2	8	3	1.14	Rate to Cotton	8.00	0.83	0.84	2.81
		CR Score	0.16	0.75	0.23		SR Score	0.83			
	Poly Propylene	Rate to Poly Propylene	5	3	5	1.055	Rate to Poly Propylene	4.00	0.42	0.84	2.31
		CR Score	0.39	0.28	0.38		SR Score	0.42			

Table 6.20
MPS Stage of CSRE Matrix

CSRE MATRIX FOR MANUFACTURING PROCESS SELECTION - UMBRELLA CLOTH											
Design Options	Material Options	Manufacturing Process Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	Previous Path Score	CSRE Score
			CR Weight	0.20		SR Weight	0.03	0.12			
			BPWCR	0.50		BPWSR	0.50	0.50			
Circular Cloth	Nylon	Nylon Production & Stitching	Rate to Nylon	8.00	0.83	Rate to Nylon	4.00	6.00	0.42	2.73	3.96
			CR Score	0.81		SR Score	0.05	0.37			
	Pongee	Pongee Production & Stitching	Rate to Pongee	6.00	0.61	Rate to Pongee	2.00	2.00	0.15	2.05	2.80
			CR Score	0.61		SR Score	0.03	0.12			
	Cotton	Cotton Production & Stitching	Rate to Cotton	4.00	0.40	Rate to Cotton	8.00	6.00	0.48	2.55	3.43
			CR Score	0.40		SR Score	0.11	0.36			
	Poly Propylene	Poly Propylene Production & Stitching	Rate to Poly Propylene	3.00	0.30	Rate to Poly Propylene	5.00	4.00	0.31	2.05	2.67
			CR Score	0.30		SR Score	0.07	0.24			
Circular Cloth with frill	Nylon	Nylon Production & Stitching	Rate to Nylon	3	0.30	Rate to Nylon	3.00	4.00	0.28	2.98	3.57
			CR Score	0.30		SR Score	0.04	0.24			
	Pongee	Pongee Production & Stitching	Rate to Pongee	1	0.10	Rate to Pongee	2.00	3.00	0.21	2.30	2.61
			CR Score	0.10		SR Score	0.03	0.18			
	Cotton	Cotton Production & Stitching	Rate to Cotton	3	0.30	Rate to Cotton	2.00	2.00	0.15	2.81	3.26
			CR Score	0.30		SR Score	0.03	0.12			
	Poly Propylene	Poly Propylene Production & Stitching	Rate to Poly Propylene	2	0.20	Rate to Poly Propylene	3.00	3.00	0.22	2.31	2.74
			CR Score	0.20		SR Score	0.04	0.18			

Table 6.21
US Stage of CSRE Matrix

CSRE MATRIX FOR USAGE SELECTION - UMBRELLA CLOTH											
Design Options	Material Options	Manufacturing Process Options	Usage Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	PPS	CSRE Score
				CR Weight	0.06		SR Weight	0.15			
				BPWCR	0.50		BPWSR	0.50			
Circular Cloth	Nylon	Nylon Production & Stitching	All Seasons	Rate to life span	8.00	0.25	Rate to Nylon	4	0.30	3.95	4.51
				CR Score	0.25		SR Score	0.30			
	Pongee	Pongee Production & Stitching	All Seasons	Rate to life span	6.00	0.19	Rate to Pongee	2	0.15	2.80	3.14
				CR Score	0.19		SR Score	0.15			
	Cotton	Cotton Production & Stitching	All Seasons	Rate to life span	4.00	0.13	Rate to Cotton	8	0.603	3.43	4.16
				CR Score	0.13		SR Score	0.60			
	Poly Propylene	Poly Propylene Production & Stitching	All Seasons	Rate to life span	3.00	0.09	Rate to Poly Propylene	5	0.37	2.67	3.14
				CR Score	0.10		SR Score	0.38			
Circular Cloth with frill	Nylon	Nylon Production & Stitching	All Seasons	Rate to life span	3	0.09	Rate to Nylon	3	0.23	3.57	3.89
				CR Score	0.09		SR Score	0.23			
	Pongee	Pongee Production & Stitching	All Seasons	Rate to life span	1	0.03	Rate to Pongee	2	0.15	2.61	2.79
				CR Score	0.03		SR Score	0.15			
	Cotton	Cotton Production & Stitching	All Seasons	Rate to life span	3	0.09	Rate to Cotton	2	0.15	3.26	3.51
				CR Score	0.09		SR Score	0.15			
	Poly Propylene	Poly Propylene Production & Stitching	All Seasons	Rate to life span	2	0.06	Rate to Poly Propylene	3	0.23	2.74	3.03
				CR Score	0.06		SR Score	0.23			

Table 6.22
DiS Stage of CSRE Matrix

CSRE Matrix for Disposal Selection – Umbrella Cloth													
Design Options	Material Options	Manufacturing Process Options	Usage Options	Disposal Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	PPS	CSRE Score
					CR Weight	0.03		SR Weight	0.19	0.21			
					BPWCR	0.50		BPWSR	0.50	0.50			
Circular Cloth	Nylon	Nylon Production & Stitching	All seasons	Recycle	Rating to Recycle	4.00	0.06	Rating to Reuse	1.00	5.00	0.62	4.51	5.18
					CR Score	0.06		SR Score	0.09	0.52			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	1.00	1.00	0.20	4.51	4.72
					CR Score	0.01		SR Score	0.09	0.10			
	Pongee	Pongee Production & Stitching	All seasons	Recycle	Rating to Recycle	1.00	0.01	Rating to Reuse	1.00	2.00	0.30	3.14	3.46
					CR Score	0.01		SR Score	0.09	0.21			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	1.00	1.00	0.20	3.14	3.35
					CR Score	0.01		SR Score	0.09	0.10			
	Cotton	Cotton Production & Stitching	All seasons	Recycle	Rating to Recycle	1.00	0.01	Rating to Reuse	1.00	1.00	0.20	4.16	4.37
					CR Score	0.01		SR Score	0.09	0.10			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	8.00	1.00	0.85	4.16	5.03
					CR Score	0.01		SR Score	0.75	0.10			
	Poly Propylene	Poly Propylene Production & Stitching	All seasons	Recycle	Rating to Recycle	4.00	0.06	Rating to Reuse	1.00	5.00	0.62	3.14	3.81
					CR Score	0.06		SR Score	0.09	0.52			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	1.00	1.00	0.198	3.14	3.35
					CR Score	0.01		SR Score	0.09	0.10			
Circular Cloth with frill	Nylon	Nylon Production & Stitching	All seasons	Recycle	Rating to Recycle	4	0.056	Rating to Reuse	1.00	5.00	0.615	3.89	4.56
					CR Score	0.06		SR Score	0.09	0.52			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	1.00	1.00	0.19	3.89	4.10
					CR Score	0.01		SR Score	0.09	0.10			
	Pongee	Pongee Production & Stitching	All seasons	Recycle	Rating to Recycle	1	0.01	Rating to Reuse	1.00	2.00	0.30	2.79	3.11
					CR Score	0.01		SR Score	0.09	0.21			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	1.00	1.00	0.21	2.80	3.02
					CR Score	0.01		SR Score	0.09	0.10			
	Cotton	Cotton Production & Stitching	All seasons	Recycle	Rating to Recycle	1	0.01	Rating to Reuse	1.00	1.00	0.198	3.51	3.72
					CR Score	0.01		SR Score	0.09	0.10			
				Dispose	Rating to Disposal	1.00	0.01	Rating to Disposal	8.00	1.00	0.85	3.507	4.37
					CR Score	0.01		SR Score	0.75	0.10			
	Poly Propylene	Poly Propylene Production & Stitching	All seasons	Recycle	Rating to Recycle	1.00	0.01	Rating to Reuse	1.00	5.00	0.615	3.026	3.65
					CR Score	0.01		SR Score	0.09	0.52			
				Dispose	Rating to Disposal	1	0.01	Rating to Disposal	1.00	1.00	0.20	3.03	3.24
					CR Score	0.01		SR Score	0.09	0.10			

The best options in each stage of PDC for each component were found out. The PDC options with maximum ‘CSRE Score’ of each component were considered initially for the product development. The maximum CSRE Score obtained was 5.18. These options were cross examined for compatibility check and found compatible with each other. The best PDC options of Umbrella Cloth is circular shaped cloth with Nylon as material, Nylon production and stitching as manufacturing process, all seasons as usage and recycling as disposal selection was compatible with the best PDC options of Ribs and Stretchers as rectangular shaped design, fiber reinforced plastic as material, extrusion as manufacturing process, all seasons as usage and recycle as disposal selection.

Compatibility checking with other components PDC options were also carried out and found compatible with each other. ‘CSRE Matrix’ for the DrS stage was developed separately as it is common for all the components. Table 6.23 shows the DrS stage CSRE Matrix. The distribution of product using wrapping machine was selected for the distribution purpose.

Table 6.23
DrS Stage CSRE Matrix

CSRE Matrix for Distribution Selection								
Distribution Options	CRs	RPC	Total CR Score	SRs	MR	MD	Total SR Score	CSRE Score
	CR Weight	1.00		SR Weight	0.50	0.50		
	BPWCR	0.50		BPWSR	0.50			
Plastic Bag	Rating to Plastic Bag	4.00	2.00	Rating to Plastic Bag	6.00	3.00	2.25	4.25
	CR Score	2.00		SR Score	1.50	0.75		
Plastic Wrapping	Rating to Plastic Wrapping	6.00	3.00	Rating to Plastic Wrapping	3.00	8.00	2.75	5.75
	CR Score	3.00		SR Score	0.75	2.00		

6.4 RESULTS AND DISCUSSION

The effectiveness of implementing CSRE Matrix with FAHP method was assessed by collecting the feedback from experts. The main aim of conducting the feedback section was to realize expert's opinion on the functionality of the proposed tool and its usefulness in achieving a customer satisfied sustainable product.

Table 6.24
Expert's feedback on 'CSRE Matrix'

Sr. No.	Question	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Average	Range
1	To what extent you support that the proposed tool can be used for the development of a sustainable and customer satisfied product in your organization?	7	6	6	7	7	7	5	7	7	6.56	2
2	To what extent you support that the proposed tool is assessing the alternative options in PDC stages based on customer requirements considered?	7	7	6	6	7	6	7	7	7	6.67	1
3	To what extent you support that the proposed tool is assessing the alternative options in PDC stages based on sustainability requirements considered?	7	7	6	6	7	7	6	6	7	6.55	1

The design team and an executive panel comprising five other senior personnel from different departments have participated in the feedback. Three questions were asked to the nine experts who have participated in the implementation study. The respondents were asked to give their opinion on a likert scale of 1 to 9, where a response of 1 indicate the disagreement and 9 indicate complete agreement. The average score obtained for all the three questions is 6.6, with a maximum range of 2. This indicated that the respondents agree that the proposed CSRE Matrix can be used as a tool for sustainable product development. The feedback summary is shown in Table 6.24. The feedback result indicates that the proposed tool is accepted by the panel of experts.

6.5 CHAPTER SUMMARY

CSRE Matrix is a generic tool which can be used for any type of product development. The development of CSRE Matrix with FAHP method and its implementation study in an umbrella manufacturing company is described in this chapter. The practitioners have accepted this tool as a method for developing customer satisfying sustainable product.

CHAPTER 7

DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR THE CSRE MATRIX

7.1 PREAMBLE

Decision Support Systems (DSSs) are computer programmed data analyzing techniques that facilitate solving complex problems (Shalij, 2009). Many DSSs have been proposed in the literature to analyze environmental and economic impacts of products and processes. Many of the eco-design tools are equipped with a Decision Support System (DSS) that assist advanced computing, modeling and optimization (Despeiss 2011). Various methods developed in a wide range of domains made DSS a broader concept (Sokolova and Fernandez-Caballero, 2009). DSS in its present form helps to perform activities such as assessing data, realizing its significance and help managers aiming at inferences to make intelligent decisions (Yoon et al., 2008). DSS not only act as a support tool for designer in analyzing data but also help to arrive at possible solutions in the complex situations.

This chapter explains the DSS developed for implementing CSRE Matrix. This DSS assists the designers to construct CSRE Matrices for different product development cycles effortlessly. In the DSS of CSRE Matrix, voice of customers (VoC) and voice of sustainability (VoS) are analyzed separately to select best options in each product development stage that help developing new product. VoC, VoS and sub-elements of VoC and VoS are weighed using Rank Order Centroid (ROC) method or Analytic Hierarchy Process (AHP) method. Various combinations of options from different stages of product development cycle are analyzed through this decision support system. Subsequent sections explain the development of CSRE Matrix as a DSS and its application in new product development through a case study.

7.2 DECISION SUPPORT SYSTEM IN SUSTAINABILITY/ENVIRONMENTAL ARENA

In a multi criteria decision making problem, the decision maker has to identify the best alternative from a number of alternatives in terms of a number of different criteria (Wei et al., 2013). It is more difficult to take a decision in sustainable development process, as it involves three different paradigms namely sustainability decision paradigm (social, economic and environment), decision making paradigm (strategic, tactical and operational) and sustainability modeling paradigm (Ahmed and Sundaram, 2012).

DSSs developed in the sustainability arena are fall in two categories. One set of DSSs help designers to evaluate the sustainability aspects where other categories of tools assist in developing sustainable products. Software tools that evaluate products and process in terms of sustainability and LCA are developed for analyzing existing products. Software tools namely GaBi, SimaPro and TRACI belong to this group. These tools assist the designers to evaluate environmental performances of existing products and processes. These DSSs have a strong data base that contains relevant data of products in terms of sustainability and environmental indicators. Many other simplified LCA methods such as ABC analysis, Eco-compass, ‘Life cycle index’ are also supported in these software tools. Software tools that help in formulating and evaluating design alternatives are developed for facilitating the designers. Tools such as DESSAS, ENVOPExpert are examples of this group (Carvalho et al., 2013).

Monitoring and maintaining the environmental performance of products and processes are the other challenges encountered in many of the manufacturing industries. To take timely decisions on these challenges, organizations require DSSs and supporting tools. LCA is one of such quantitative tool (Abdalla et al., 2012). Similarly, many market based DSS methodologies have been reported in the literatures that are intended to focus on product and process selection (Besharati et al., 2006).

Khan et al., (2004) has developed a decision making system called ‘Life cycle index’ (LinX) in which environment, cost, technology and socio-political factors are considered for decision making by comparing alternative designs of products and processes. Moskowitz and Kim (1997) have developed a tool named ‘QFD optimizer’ for supporting the design team to build house of quality chart to get engineering characteristic values. This decision support system helps the designer to find feasible design options with higher customer satisfaction. Besharati et al., (2006) have developed a DSS for selecting the final design of a new product based on market demand, designer’s preferences and uncertainty in the achievement of predicted design.

Decision making with accuracy is always a daunting task in product development particularly to select an option from many. Prior to selection of the best option, designers have to answer myriads of questions related to its customer requirements, regulatory requirements, organizational restrictions on production, profit margins and quality, market demand, environmental requirements, local society requirements, product life span, maintenance requirement, end of life decisions etc. Trade-offs between different requirements is the only possible method in such situations (Byggeth and Hochschorner, 2006). Multi-criteria decision tools such as Analytic Hierarchy Process (AHP), Conjoint Analysis (CA), Rank Order Centroid (ROC) weight method, Fuzzy Analytic Hierarchy

Process (FAHP), Multi Attribute Utility Theory (MAUT) etc assist the designers in achieving this objective.

Prioritization of options or criteria or objectives is generally carried out by means of multi-criteria decision tools. The DSS system proposed in this doctoral work employs two multi-criteria decision support tools namely ROC weights method and AHP. The following sections explain the development of DSS of CSRE Matrix using these two multi-criteria decision support tools.

7.3 DECISION SUPPORT SYSTEM OF CSRE MATRIX

Decision Support System of CSRE Matrix (herein after referred as ‘CSREMDSS’) facilitates carrying out various steps included in CSRE Matrix. Once the required information is given to CSREMDSS, all the computations involved in the CSRE Matrix will be carried out by the system. The system also generates necessary reports at the end. The CSREMDSS home screen is shown in Fig. 7.1.

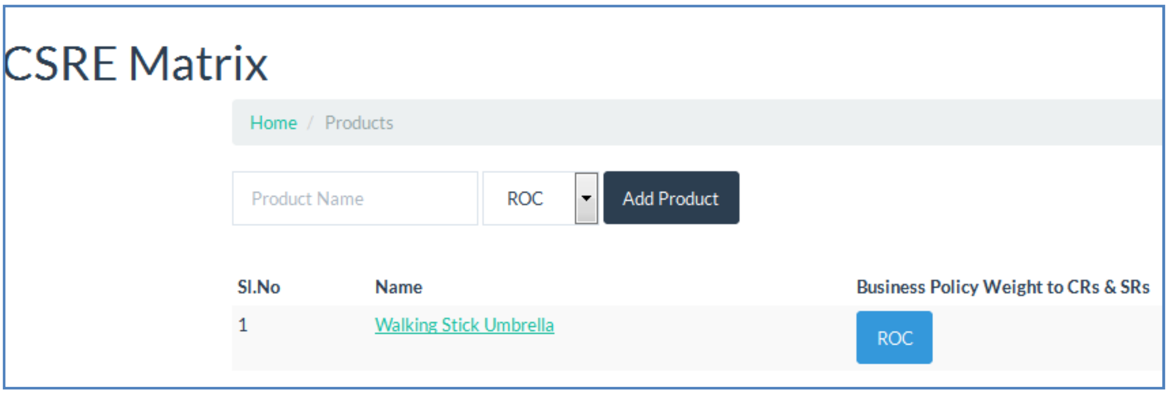
Customer and Sustainability Requirement Evaluation Matrix (CSRE Matrix)

Figure 7.1 CSREMDSS Home Screen.

New product development using CSREMDSS is carried out using the same steps as explained in Chapter 3, Section 3.2 for CSRE Matrix. However, to facilitate the user interface, slight deviations have been made in CSREMDSS from the original CSRE Matrix construction. The major change in the CSREMDSS is that some steps of CSRE Matrix construction are carried out using a single user interface in CSREMDSS.

The first step in the CSREMDSS is to enter the details of the product identified for developing the CSRE Matrix. Figure 7.2 shows the designer interface to enter these details of the products. Each product entry will be saved as a separate file and can be retrieved at any time.

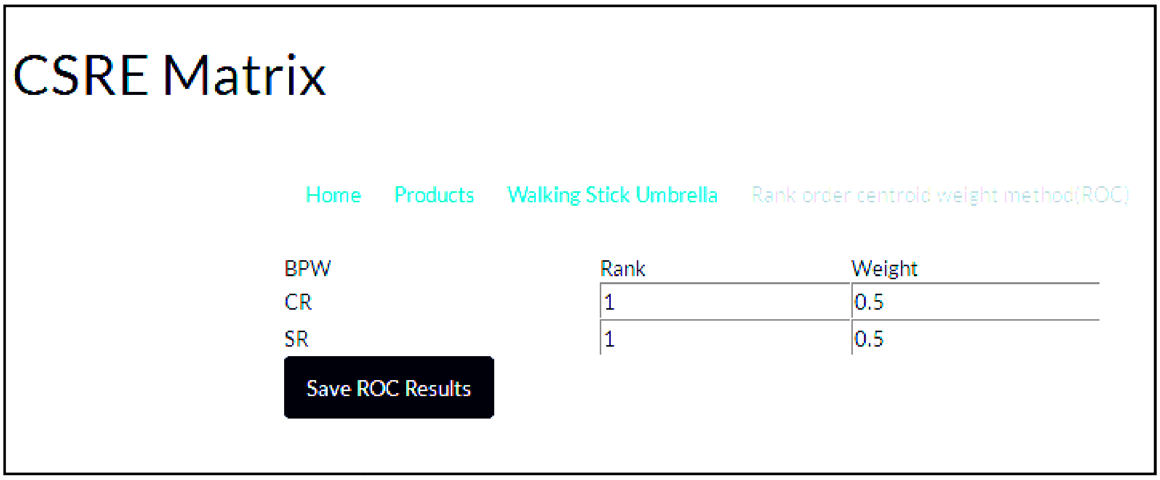
In the same user interface of CSREMDSS, designer is offered two options of multi criteria-decision support tools namely ROC weight method and AHP method. Designer has to select any one of the options from these methods. These two multi criteria-decision support tools are used to calculate Business policy weight to CRs and SRs and also for weighing CRs and SRs. The selected multi criteria-decision support tool will be used throughout the CSRE Matrix development process for that particular product. CSREMDSS screen shots shown in this chapter are related to the component ‘umbrella cloth’ of the product ‘walking stick umbrella’ described in chapter 6.



CSRE Matrix

Sl.No	Name	Business Policy Weight to CRs & SRs
1	Walking Stick Umbrella	ROC

Figure 7.2 CSREMDSS - Product entry



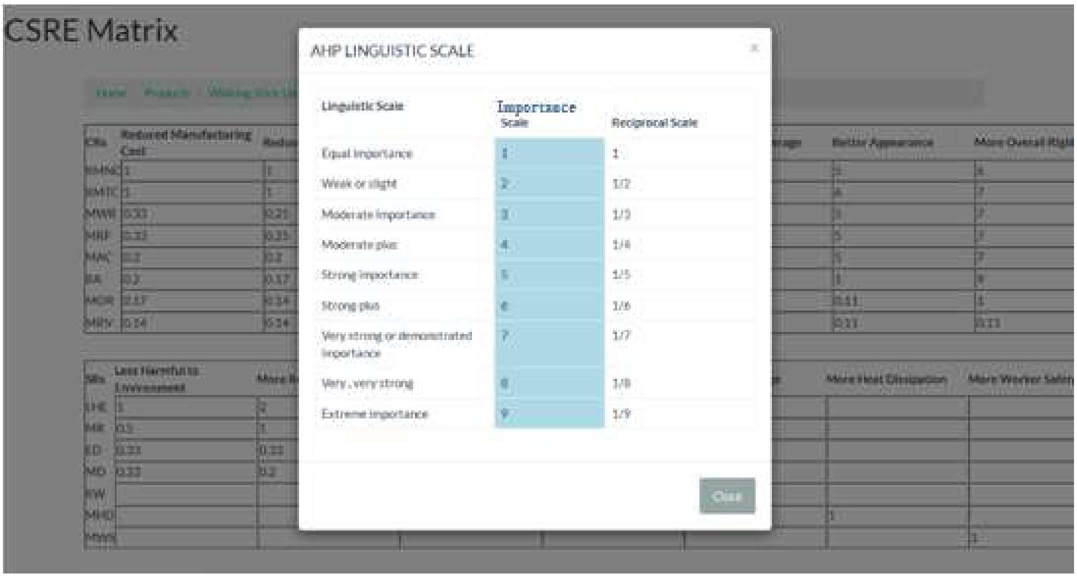
CSRE Matrix

BPW	Rank	Weight
CR	1	0.5
SR	1	0.5

Figure 7.3 CSREMDSS – User interface for weighing CRs and SRs

The organization may have different policies on prioritizing CRs and SRs. In these cases, Business Policy Weight (BPW) to CRs and SRs may vary. If the designer select ROC method in CSREMDSS, the user interface will ask for ranking CRs and SRs. Once the ranking is given, the system will generate Business Policy Weight to CR and SR (BPWCR and BPWSR respectively) using the ROC weights formula. Figure 7.3 shows the BPWCR and BPWSR calculated by the CSREMDSS. When equal importance was given to both CRs and SRs, the weights obtained were 0.5 each.

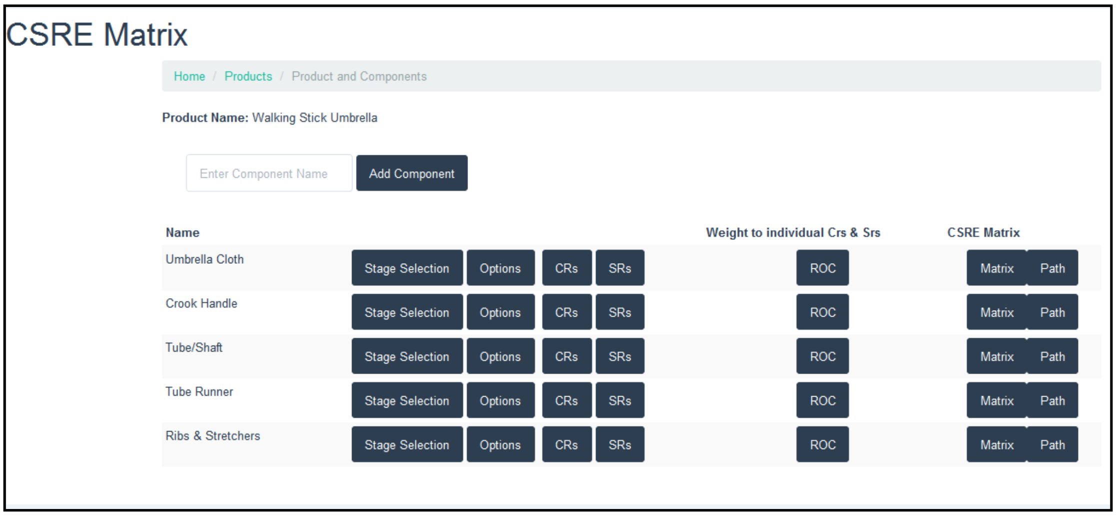
If the designer select AHP method in CSREMDSS, the user interface will ask for ranking CRs and SRs. Then a pair-wise comparison matrix will appear in the screen. The designer has to select appropriate importance rating based on the linguistic scale that appears in the screen. For assisting designer to input importance rating, a drop down menu as shown in Fig. 7.4 will appear on the screen, from which designer can select the importance rating.



Linguistic Scale	Importance Scale	Reciprocal Scale
Equal importance	1	1
Weak or slight	2	1/2
Moderate importance	3	1/3
Moderate plus	4	1/4
Strong importance	5	1/5
Strong plus	6	1/6
Very strong or demonstrated importance	7	1/7
Very , very strong	8	1/8
Extreme importance	9	1/9

Figure 7.4 CSREMDSS – drop down menu

Once the importance weights to BPWCR and BPWSR are calculated by the system, designer has to add components of the product and identify the PDC stages applicable for the product/component. Against each component, a PDC stage selection option button will be appeared captioned ‘stage selection’ as shown in Fig. 7.5. All the PDC stages applicable in CSRE Matrix will be displayed in this CSREMDSS interface when the designer selects this button against each component. The PDC stages for each component are selected accordingly and saved.

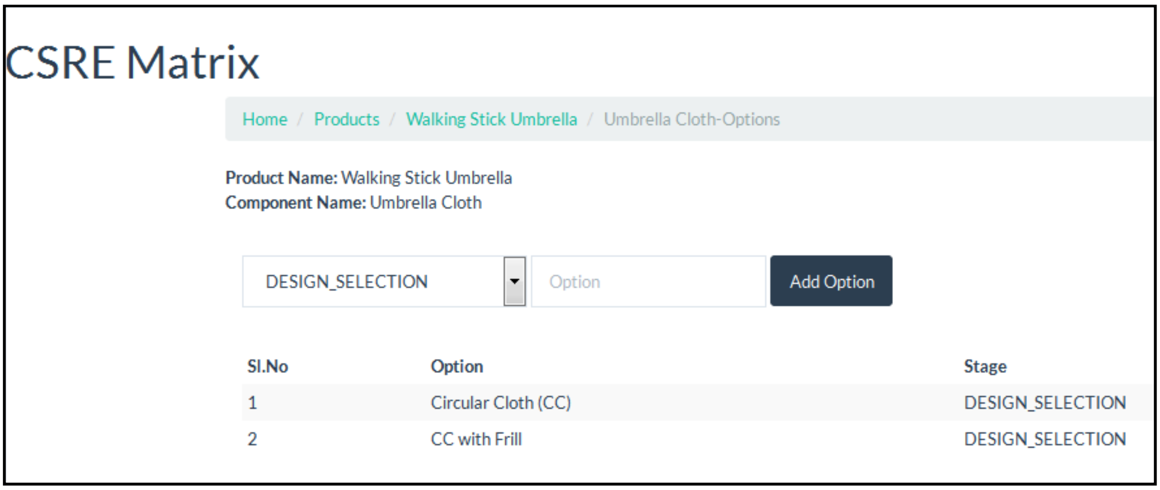


Product Name: Walking Stick Umbrella

Name		Weight to individual Crs & Srs	CSRE Matrix
Umbrella Cloth	Stage Selection Options CRs SRs	ROC	Matrix Path
Crook Handle	Stage Selection Options CRs SRs	ROC	Matrix Path
Tube/Shaft	Stage Selection Options CRs SRs	ROC	Matrix Path
Tube Runner	Stage Selection Options CRs SRs	ROC	Matrix Path
Ribs & Stretchers	Stage Selection Options CRs SRs	ROC	Matrix Path

Figure 7.5 CSREMDSS - user interface to add components, PDC Options, CRs, SRs

As seen in Fig. 7.5, the button captioned ‘option’ has to be selected by the designer as a next step, for adding the different options identified under each PDC stages. In the pop up screen, the designer has to add these options against each component and save the data. Figure 7.6 shows the CSRE Matrix screen shot after selecting options under design selection stage. Similarly, Fig. 7.7 shows the CSRE Matrix screen shot after selecting options under all the stages of PDC.

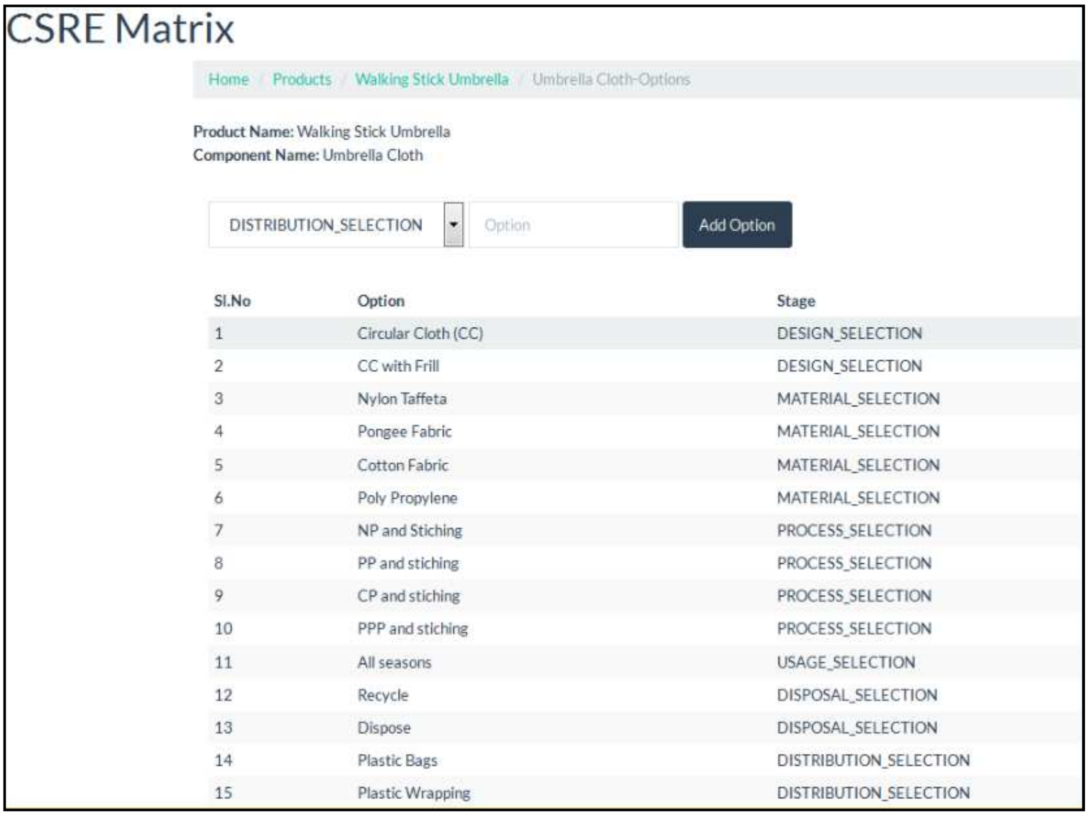


Product Name: Walking Stick Umbrella
Component Name: Umbrella Cloth

Sl.No	Option	Stage
1	Circular Cloth (CC)	DESIGN_SELECTION
2	CC with Frill	DESIGN_SELECTION

Figure 7.6 CSREMDSS – Options selected under Design Selection Stage

The CRs identified under each PDC stages are then entered against each component. SRs identified are also subsequently entered by the designer against each component. Designer then ranks each CR. If all the members of design team are present while entering the ranks, the user interface helps them to identify components and their PDC options by discussing and arriving at a consensus for comparing CRs and subsequent ranking. Figure 7.8 shows the screen shot after completing this endeavor for the component umbrella cloth.

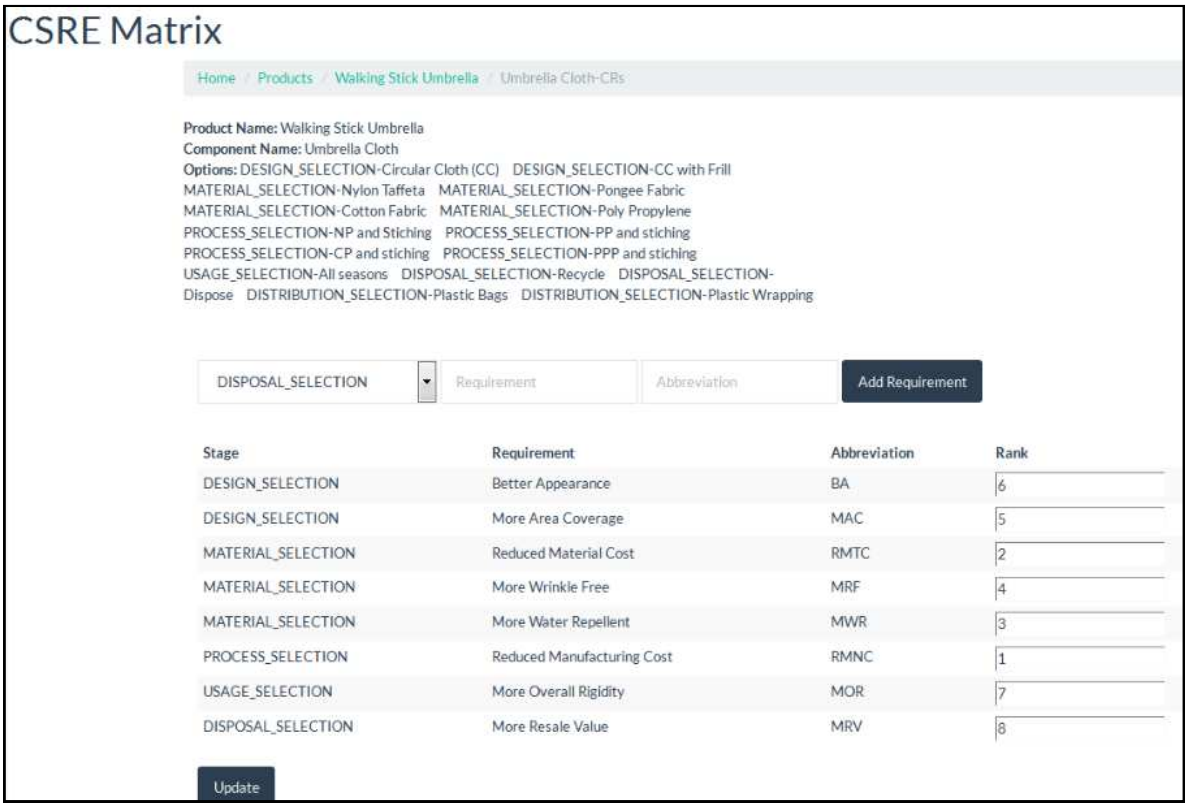

CSRE Matrix

Product Name: Walking Stick Umbrella
Component Name: Umbrella Cloth

Sl.No	Option	Stage
1	Circular Cloth (CC)	DESIGN_SELECTION
2	CC with Frill	DESIGN_SELECTION
3	Nylon Taffeta	MATERIAL_SELECTION
4	Pongee Fabric	MATERIAL_SELECTION
5	Cotton Fabric	MATERIAL_SELECTION
6	Poly Propylene	MATERIAL_SELECTION
7	NP and Stiching	PROCESS_SELECTION
8	PP and stiching	PROCESS_SELECTION
9	CP and stiching	PROCESS_SELECTION
10	PPP and stiching	PROCESS_SELECTION
11	All seasons	USAGE_SELECTION
12	Recycle	DISPOSAL_SELECTION
13	Dispose	DISPOSAL_SELECTION
14	Plastic Bags	DISTRIBUTION_SELECTION
15	Plastic Wrapping	DISTRIBUTION_SELECTION

Figure 7.7 CSREMDSS – Options selected under each PDC stage

Similarly SRs identified undereach component and their ranks are entered by the designer. Figure 7.9 shows the SRs and their rankings entered for the component umbrella cloth.

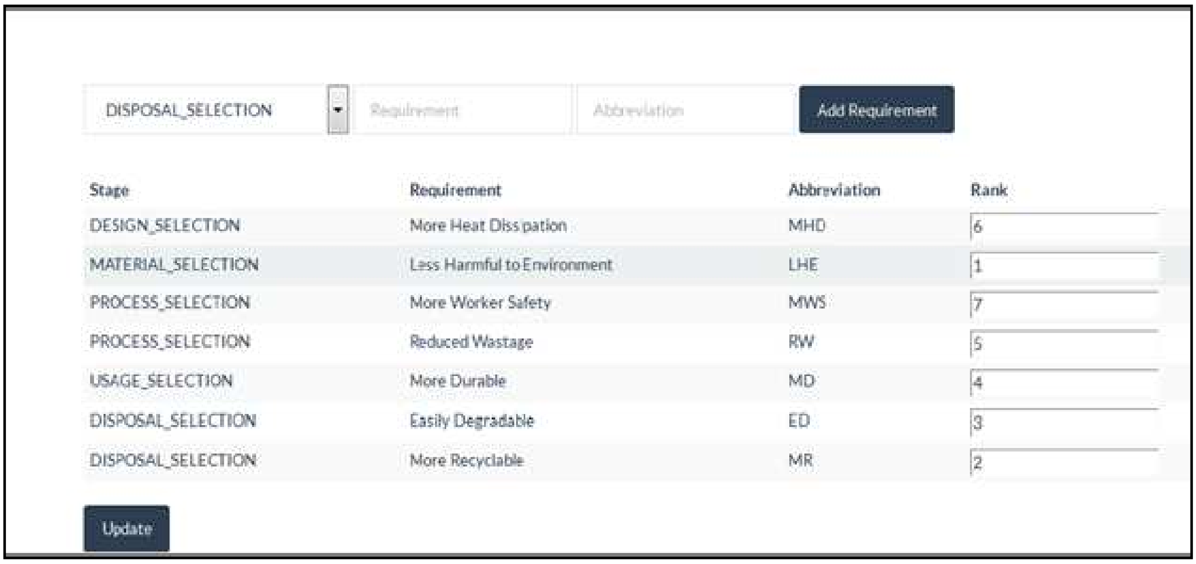


CSRE Matrix

Product Name: Walking Stick Umbrella
Component Name: Umbrella Cloth
Options: DESIGN_SELECTION-Circular Cloth (CC) DESIGN_SELECTION-CC with Frill MATERIAL_SELECTION-Nylon Taffeta MATERIAL_SELECTION-Pongee Fabric MATERIAL_SELECTION-Cotton Fabric MATERIAL_SELECTION-Poly Propylene PROCESS_SELECTION-NP and Stiching PROCESS_SELECTION-PP and stiching PROCESS_SELECTION-CP and stiching PROCESS_SELECTION-PPP and stiching USAGE_SELECTION-All seasons DISPOSAL_SELECTION-Recycle DISPOSAL_SELECTION-Dispose DISTRIBUTION_SELECTION-Plastic Bags DISTRIBUTION_SELECTION-Plastic Wrapping

Stage	Requirement	Abbreviation	Rank
DESIGN_SELECTION	Better Appearance	BA	6
DESIGN_SELECTION	More Area Coverage	MAC	5
MATERIAL_SELECTION	Reduced Material Cost	RMTC	2
MATERIAL_SELECTION	More Wrinkle Free	MRF	4
MATERIAL_SELECTION	More Water Repellent	MWR	3
PROCESS_SELECTION	Reduced Manufacturing Cost	RMNC	1
USAGE_SELECTION	More Overall Rigidity	MOR	7
DISPOSAL_SELECTION	More Resale Value	MRV	8

Figure 7.8 CSREMDSS – CRs selected under each PDC stage and their ranking



Stage	Requirement	Abbreviation	Rank
DESIGN_SELECTION	More Heat Dissipation	MHD	6
MATERIAL_SELECTION	Less Harmful to Environment	LHE	1
PROCESS_SELECTION	More Worker Safety	MWS	7
PROCESS_SELECTION	Reduced Wastage	RW	5
USAGE_SELECTION	More Durable	MD	4
DISPOSAL_SELECTION	Easily Degradable	ED	3
DISPOSAL_SELECTION	More Recyclable	MR	2

Figure 7.9 CSREMDSS – SRs selected under each PDC stage and their ranking

Upon entering the ranks against CRs and SRs, CSREMDSS compute the weights either using ROC weight method or by AHP methods, as per the method selected initially.

If the designer select AHP method, similar to BPWCR and BPWSR calculation, a dropdown menu will be appeared in the CSREMDSS interface that will help the designer to input importance rating based on linguistic scales. Figure 7.10 shows the screen shot of CSREMDSS interface, after the weights were calculated for CRs and SRs using ROC weights method.

CSRE Matrix

Rank order centroid weight method(ROC)

CRs	Rank	Weight
BA	6	0.05
MAC	5	0.08
RMTC	2	0.21
MRF	4	0.11
MWR	3	0.15
RMNC	1	0.34
MOR	7	0.03
MRV	8	0.02

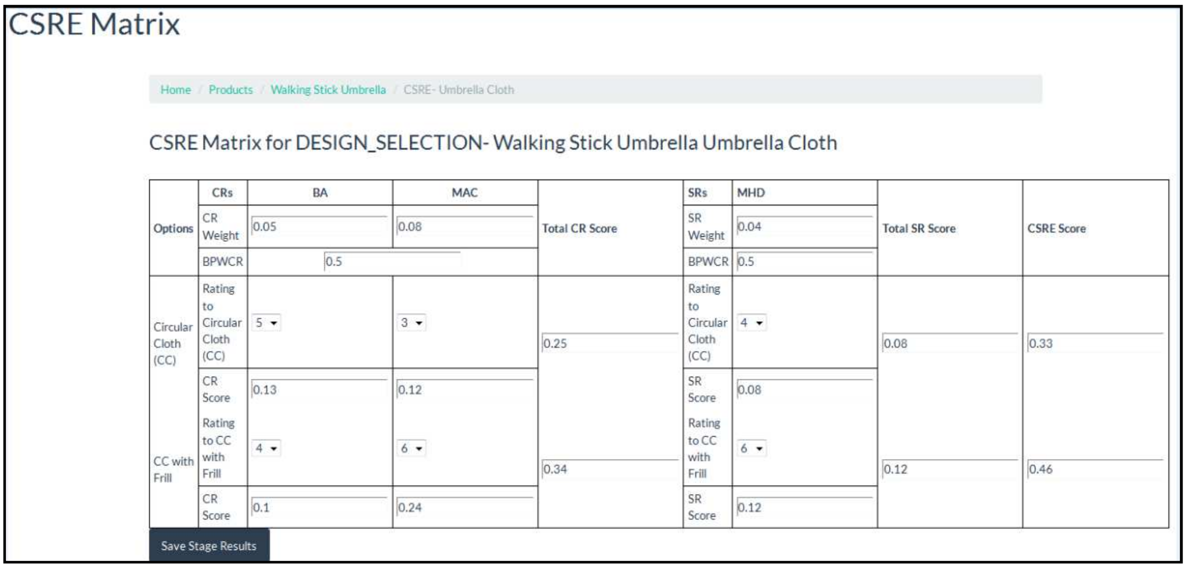
SRs	Rank	Weight
MHD	6	0.04
LHE	1	0.37
MWS	7	0.02
RW	5	0.07
MD	4	0.11
ED	3	0.16
MR	2	0.23

Figure 7.10 CSREMDSS – Weights of CRs and SRs

CSREMDSS in the same manner as explained in section 3.2 is carried out for the CSRE Matrix Phase 2. Once the weights for CRs and SRs are determined, the first phase of the CSRE Matrix is completed. The designer has to go back to the product and components page to start the second phase of CSRE Matrix. When the designer selects the matrix button in the product and component page (Fig. 7.5), matrices corresponding to PDC stages will be appeared against each component.

Initially the CSRE Matrix for the first stage namely Design Selection (DS) has to be constructed. Subsequently, CSRE Matrices have to be constructed for ‘Material Selection’ (MS), ‘Manufacturing Process Selection’ (MPS), ‘Distribution Selection’ (DrS), ‘Usage Selection’ (US) and ‘Disposal Selection’ (DiS) stages.

The first CSRE Matrix appears in CSREMDSS interface is the DS Matrix, as it was the first PDC stage selected by the designer. In the DS Matrix screen of CSREMDSS, all the inputs given earlier by the designer will be displayed against each CR, SR and options of PDC. In the same CSREMDSS user interface, the designer has to give rating to each option against each CR and SR.

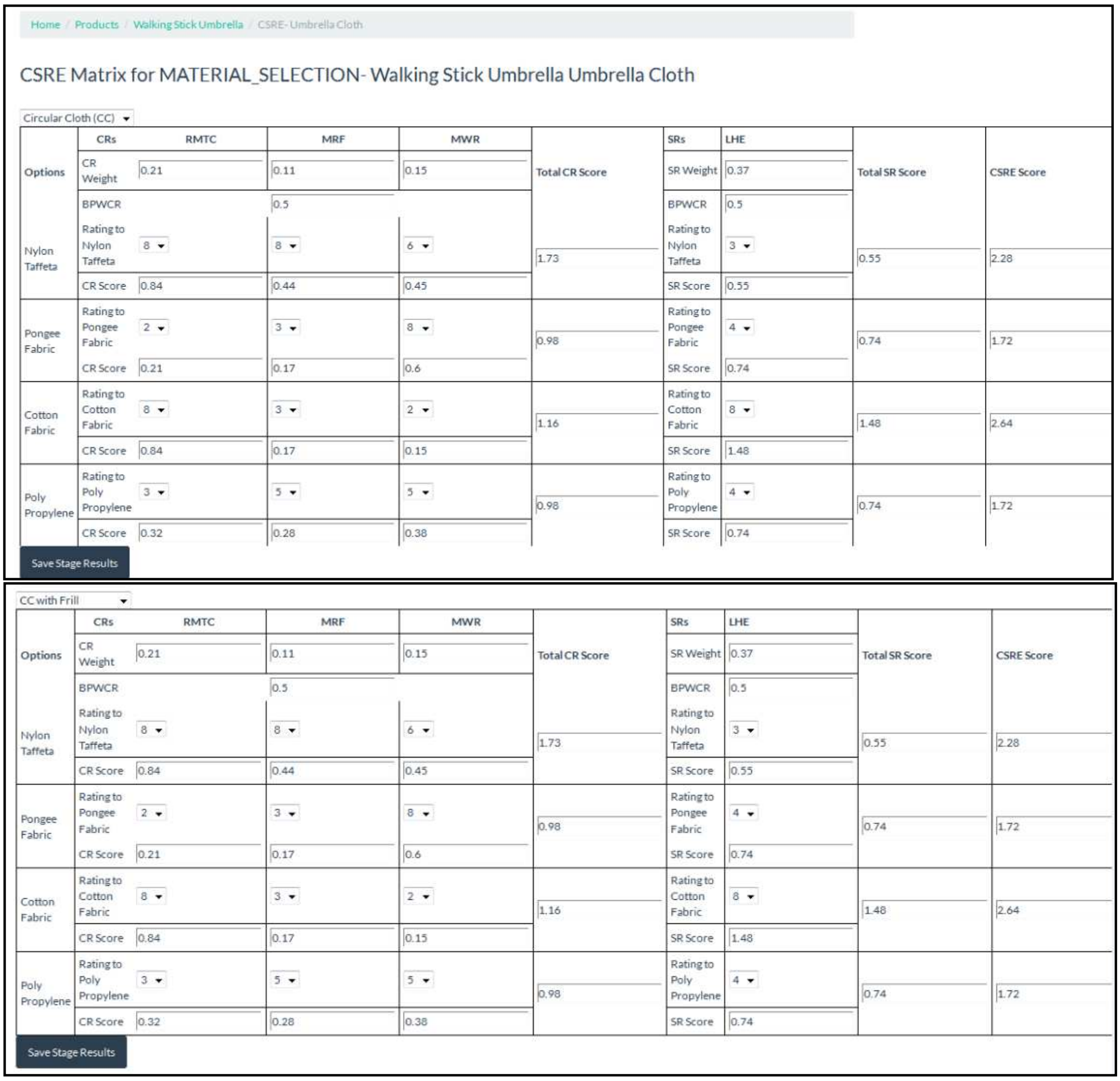


CSRE Matrix for DESIGN_SELECTION- Walking Stick Umbrella Umbrella Cloth

Options	CRs	BA	MAC	Total CR Score	SRs	MHD	Total SR Score	CSRE Score
	CR Weight	0.05	0.08		SR Weight	0.04		
	BPWCR	0.5			BPWCR	0.5		
Circular Cloth (CC)	Rating to Circular Cloth (CC)	5 ▾	3 ▾	0.25	Rating to Circular Cloth (CC)	4 ▾	0.08	0.33
	CR Score	0.13	0.12		SR Score	0.08		
CC with Frill	Rating to CC with Frill	4 ▾	6 ▾	0.34	Rating to CC with Frill	6 ▾	0.12	0.46
	CR Score	0.1	0.24		SR Score	0.12		

Figure 7.11 CSREMDSS – DS Matrix

These ratings are given by the designer using the drop down menu that appear adjacent to the box where ratings has to be given. The rating values of 1 to 9 will be appeared in a drop down menu. The calculations of total CR scores, SR scores and CSRE score will be done by the system. The CSRE Matrix of DS stage that appears in CSREMDSS is shown in Fig. 7.11.



CSRE Matrix for MATERIAL_SELECTION- Walking Stick Umbrella Umbrella Cloth

Circular Cloth (CC)

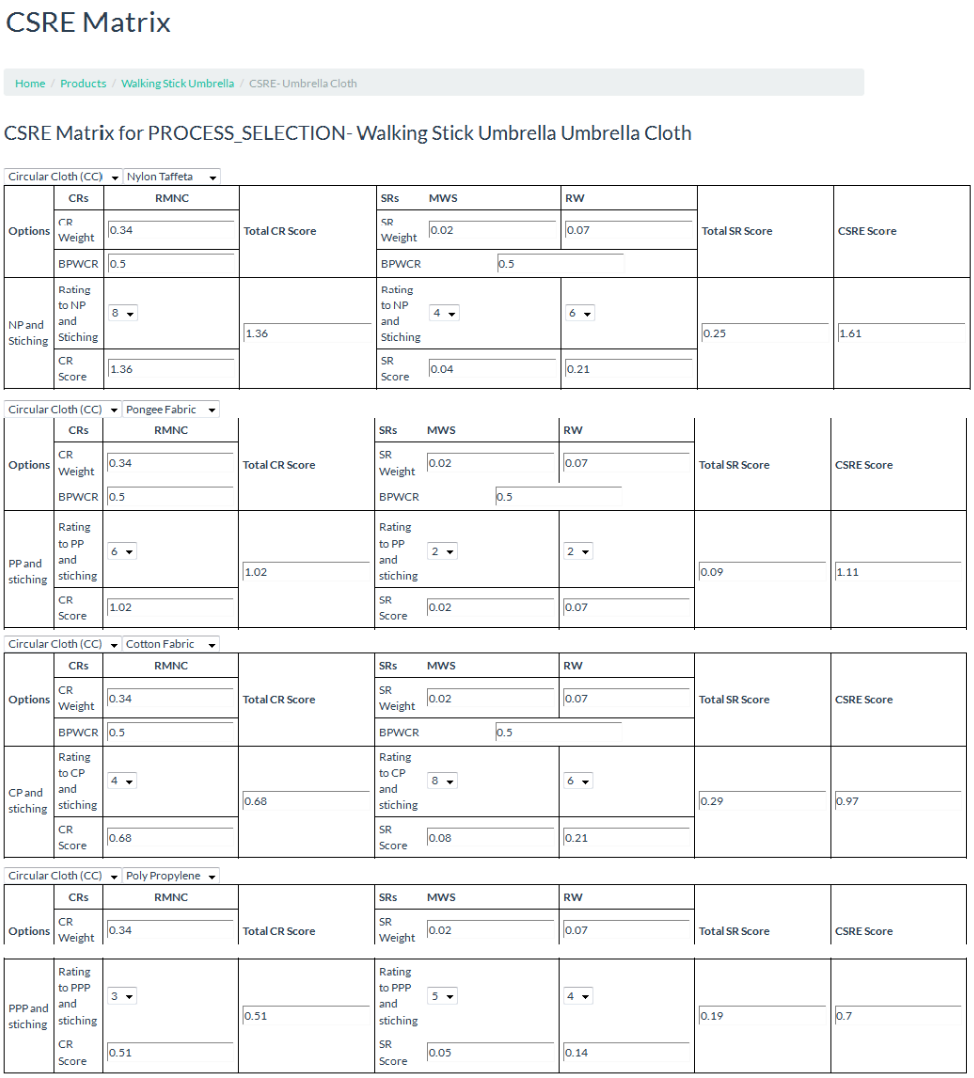
Options	CRs	RMTC	MRF	MWR	Total CR Score	SRs	LHE	Total SR Score	CSRE Score
	CR Weight	0.21	0.11	0.15		SR Weight	0.37		
	BPWCR		0.5			BPWCR	0.5		
Nylon Taffeta	Rating to Nylon Taffeta	8	8	6	1.73	Rating to Nylon Taffeta	3	0.55	2.28
	CR Score	0.84	0.44	0.45		SR Score	0.55		
Pongee Fabric	Rating to Pongee Fabric	2	3	8	0.98	Rating to Pongee Fabric	4	0.74	1.72
	CR Score	0.21	0.17	0.6		SR Score	0.74		
Cotton Fabric	Rating to Cotton Fabric	8	3	2	1.16	Rating to Cotton Fabric	8	1.48	2.64
	CR Score	0.84	0.17	0.15		SR Score	1.48		
Poly Propylene	Rating to Poly Propylene	3	5	5	0.98	Rating to Poly Propylene	4	0.74	1.72
	CR Score	0.32	0.28	0.38		SR Score	0.74		

CC with Frill

Options	CRs	RMTC	MRF	MWR	Total CR Score	SRs	LHE	Total SR Score	CSRE Score
	CR Weight	0.21	0.11	0.15		SR Weight	0.37		
	BPWCR		0.5			BPWCR	0.5		
Nylon Taffeta	Rating to Nylon Taffeta	8	8	6	1.73	Rating to Nylon Taffeta	3	0.55	2.28
	CR Score	0.84	0.44	0.45		SR Score	0.55		
Pongee Fabric	Rating to Pongee Fabric	2	3	8	0.98	Rating to Pongee Fabric	4	0.74	1.72
	CR Score	0.21	0.17	0.6		SR Score	0.74		
Cotton Fabric	Rating to Cotton Fabric	8	3	2	1.16	Rating to Cotton Fabric	8	1.48	2.64
	CR Score	0.84	0.17	0.15		SR Score	1.48		
Poly Propylene	Rating to Poly Propylene	3	5	5	0.98	Rating to Poly Propylene	4	0.74	1.72
	CR Score	0.32	0.28	0.38		SR Score	0.74		

Figure 7.12 CSREMDSS – MS Matrix

Upon completing the CSRE Matrix of DS, the designer has to save the CSRE Matrix by clicking the ‘Save Stage Result’ button displayed at the bottom of the DS Matrix. The system will subsequently direct to the next CSRE Matrix namely the MS Matrix. Similar to DS Matrix, matrices corresponding to MS, MPS, US, DiS and DrS stages also have to be developed. Figures 7.12, 7.13, 7.14, 7.15 and 7.17 depict the CSRE Matrices developed using CSREMDSS for MS, MPS, US, DiS and DrS stages respectively.



CSRE Matrix

Home / Products / Walking Stick Umbrella / CSRE- Umbrella Cloth

CSRE Matrix for PROCESS_SELECTION- Walking Stick Umbrella Umbrella Cloth

Circular Cloth (CC) Nylon Taffeta

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.34		SR Weight	0.02	0.07		
	BPWCR	0.5		BPWCR	0.5			
NP and Stiching	Rating to NP and Stiching	8	1.36	Rating to NP and Stiching	4	6	0.25	1.61
	CR Score	1.36		SR Score	0.04	0.21		

Circular Cloth (CC) Pongee Fabric

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.34		SR Weight	0.02	0.07		
	BPWCR	0.5		BPWCR	0.5			
PP and stiching	Rating to PP and stiching	6	1.02	Rating to PP and stiching	2	2	0.09	1.11
	CR Score	1.02		SR Score	0.02	0.07		

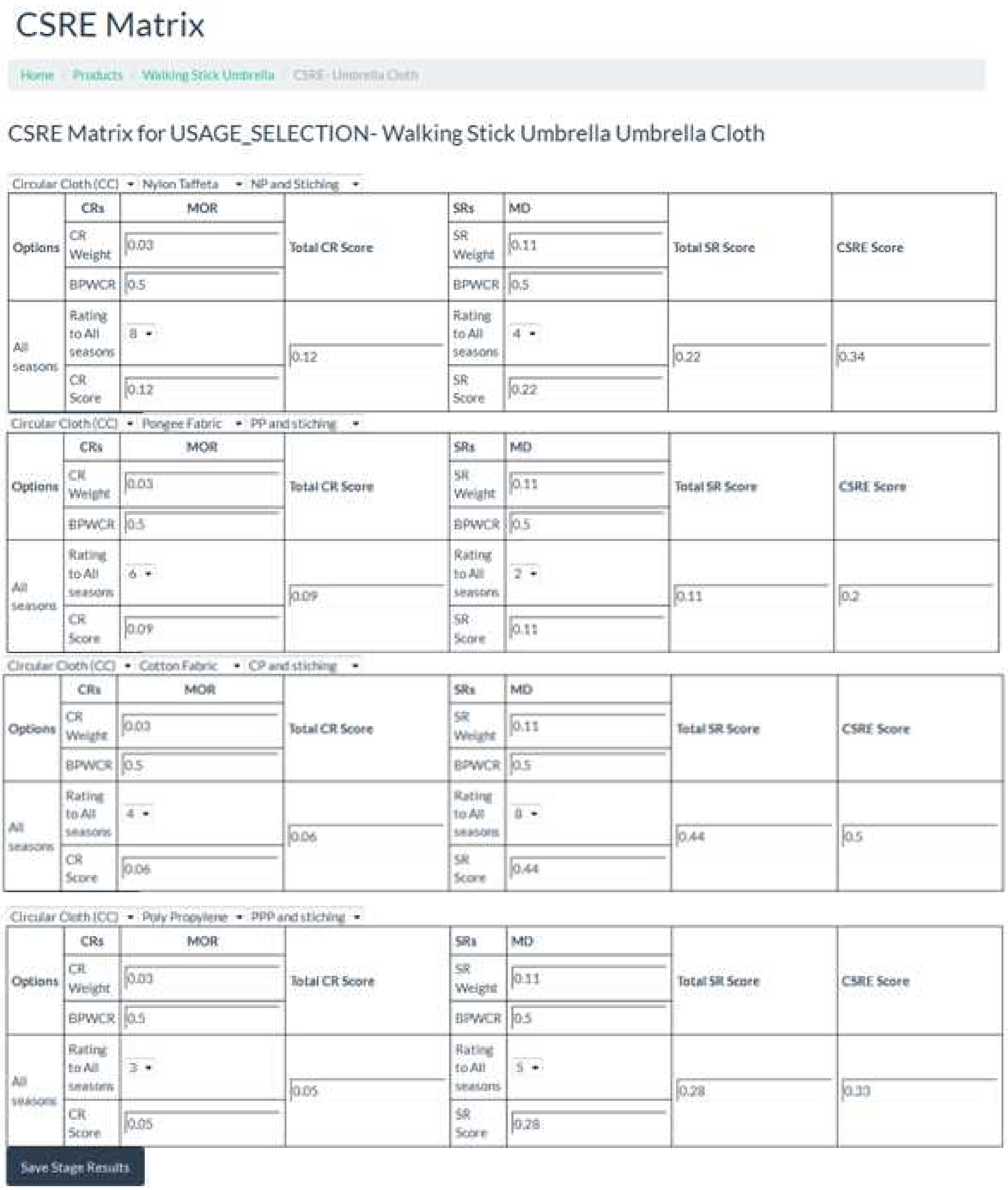
Circular Cloth (CC) Cotton Fabric

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.34		SR Weight	0.02	0.07		
	BPWCR	0.5		BPWCR	0.5			
CP and stiching	Rating to CP and stiching	4	0.68	Rating to CP and stiching	8	6	0.29	0.97
	CR Score	0.68		SR Score	0.08	0.21		

Circular Cloth (CC) Poly Propylene

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.34		SR Weight	0.02	0.07		
PPP and stiching	Rating to PPP and stiching	3	0.51	Rating to PPP and stiching	5	4	0.19	0.7
	CR Score	0.51		SR Score	0.05	0.14		

Figure 7.13 CSREMDSS – MPS Matrix



CSRE Matrix

CSRE Matrix for USAGE_SELECTION- Walking Stick Umbrella Umbrella Cloth

Circular Cloth (CC) ▾ Nylon Taffeta ▾ NP and Stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.03		SR Weight	0.11		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	8 ▾	0.12	Rating to All seasons	4 ▾	0.22	0.34
	CR Score	0.12		SR Score	0.22		

Circular Cloth (CC) ▾ Pongee Fabric ▾ PP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.03		SR Weight	0.11		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	6 ▾	0.09	Rating to All seasons	2 ▾	0.11	0.2
	CR Score	0.09		SR Score	0.11		

Circular Cloth (CC) ▾ Cotton Fabric ▾ CP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.03		SR Weight	0.11		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	4 ▾	0.06	Rating to All seasons	8 ▾	0.44	0.5
	CR Score	0.06		SR Score	0.44		

Circular Cloth (CC) ▾ Poly Propylene ▾ PPP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.03		SR Weight	0.11		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	3 ▾	0.05	Rating to All seasons	5 ▾	0.28	0.33
	CR Score	0.05		SR Score	0.28		

Figure 7.14 CSREMDSS – US Matrix

CSRE Matrix

CSRE Matrix for DISPOSAL_SELECTION- Walking Stick Umbrella Umbrella Cloth

Circular Cloth (CC) ▾ Pongee Fabric ▾ PP and stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Scor
	CR Weight	0.02		SR Weight	0.16	0.23		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	1 ▾	0.01	Rating to Recycle	1 ▾	2 ▾	0.31	0.32
	CR Score	0.01		SR Score	0.08	0.23		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.2	0.21
	CR Score	0.01		SR Score	0.08	0.12		

Circular Cloth (CC) ▾ Nylon Taffeta ▾ NP and Stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.02		SR Weight	0.16	0.23		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	4 ▾	0.04	Rating to Recycle	1 ▾	5 ▾	0.66	0.7
	CR Score	0.04		SR Score	0.08	0.58		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.2	0.21
	CR Score	0.01		SR Score	0.08	0.12		

Circular Cloth (CC) ▾ Cotton Fabric ▾ CP and stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.02		SR Weight	0.16	0.23		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	1 ▾	0.01	Rating to Recycle	1 ▾	1 ▾	0.2	0.21
	CR Score	0.01		SR Score	0.08	0.12		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	8 ▾	1 ▾	0.76	0.77
	CR Score	0.01		SR Score	0.64	0.12		

Circular Cloth (CC) ▾ Poly Propylene ▾ PPP and stiching ▾ All seasons ▾

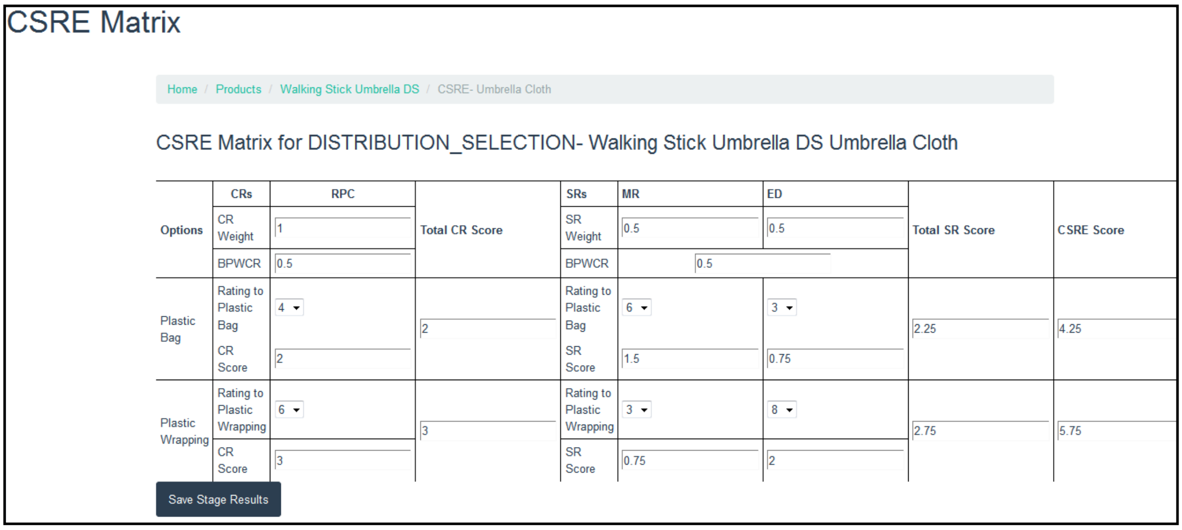
Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.02		SR Weight	0.16	0.23		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	4 ▾	0.04	Rating to Recycle	1 ▾	5 ▾	0.66	0.7
	CR Score	0.04		SR Score	0.08	0.58		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.2	0.21
	CR Score	0.01		SR Score	0.08	0.12		

Figure 7.15 CSREMDSS – DiS Matrix

After developing CSRE Matrix against each PDC stage, designer has to go back to the products and components page to select the path generation button. This is shown in Fig. 7.5 as path button. When the designer selects the path button, system will generate all the possible paths with scores against each path as shown in Fig. 7.16. The combination path Circular Cloth with Frill as design, Nylon Taffeta as material, Nylon Production and Stitching as Manufacturing Process, All season as usage and Recycle as disposal got a maximum score of 15.14 as shown in Fig. 7.16. The second combination path score obtained was 15.0 against Circular Cloth as design and Nylon Taffeta as material, Nylon Production and Stitching as Manufacturing Process, All season as usage and Recycle as disposal. DrS stage was constructed separately. Figure 7.17 shows the DrS stage Matrix. The distribution with plastic wrapping got a maximum score of 5.75.

```
Circular Cloth (CC)->Nylon Taffeta->NP and Stiching->All seasons->Recycle----
PPS(15.0)
CC with Frill->Nylon Taffeta->NP and Stiching->All seasons->Recycle----PPS(15.14)
Circular Cloth (CC)->Pongee Fabric->PP and stiching->All seasons->Recycle----
PPS(12.97)
CC with Frill->Pongee Fabric->PP and stiching->All seasons->Recycle----PPS(13.11)
Circular Cloth (CC)->Cotton Fabric->CP and stiching->All seasons->Recycle----
PPS(14.98)
CC with Frill->Cotton Fabric->CP and stiching->All seasons->Recycle----PPS(15.12)
Circular Cloth (CC)->Poly Propylene->PPP and stiching->All seasons->Recycle----
PPS(12.73)
CC with Frill->Poly Propylene->PPP and stiching->All seasons->Recycle----PPS(12.87)
Circular Cloth (CC)->Nylon Taffeta->NP and Stiching->All seasons->Dispose----
PPS(13.47)
CC with Frill->Nylon Taffeta->NP and Stiching->All seasons->Dispose----PPS(13.61)
Circular Cloth (CC)->Pongee Fabric->PP and stiching->All seasons->Dispose----
PPS(11.44)
CC with Frill->Pongee Fabric->PP and stiching->All seasons->Dispose----PPS(11.58)
Circular Cloth (CC)->Cotton Fabric->CP and stiching->All seasons->Dispose----
PPS(13.45)
CC with Frill->Cotton Fabric->CP and stiching->All seasons->Dispose----PPS(13.59)
Circular Cloth (CC)->Poly Propylene->PPP and stiching->All seasons->Dispose----
PPS(11.2)
CC with Frill->Poly Propylene->PPP and stiching->All seasons->Dispose----PPS(11.34)
```

Figure 7.16 CSREMDSS – Path with Path scores



CSRE Matrix

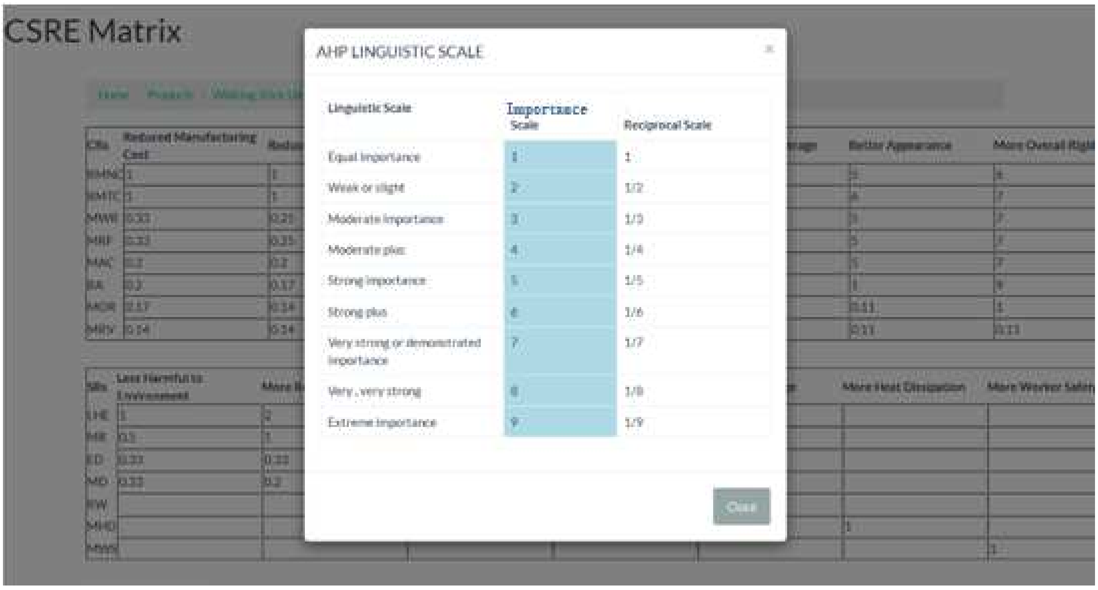
Home / Products / Walking Stick Umbrella DS / CSRE- Umbrella Cloth

CSRE Matrix for DISTRIBUTION_SELECTION- Walking Stick Umbrella DS Umbrella Cloth

Options	CRs	RPC	Total CR Score	SRs	MR	ED	Total SR Score	CSRE Score
	CR Weight	1		SR Weight	0.5	0.5		
	BPWCR	0.5		BPWCR	0.5			
Plastic Bag	Rating to Plastic Bag	4	2	Rating to Plastic Bag	6	3	2.25	4.25
	CR Score	2		SR Score	1.5	0.75		
Plastic Wrapping	Rating to Plastic Wrapping	6	3	Rating to Plastic Wrapping	3	8	2.75	5.75
	CR Score	3		SR Score	0.75	2		

Figure 7.17 CSREMDSS – DrS Matrix

Subsequently, the multi-criteria decision support tool was changed from ROC to AHP in CSREMDSS. In AHP approach, to obtain the weights to individual CRs and SRs, pair-wise comparisons were carried out. For this, importance ratings according to the linguistic variables were inserted using a drop down menu. Figure 7.18 is the screen shot that include the drop down menu for entering the linguistic variables and importance scale. Figure 7.19 is the screen shot that depicts the CRs and SRs weights calculated using AHP method.

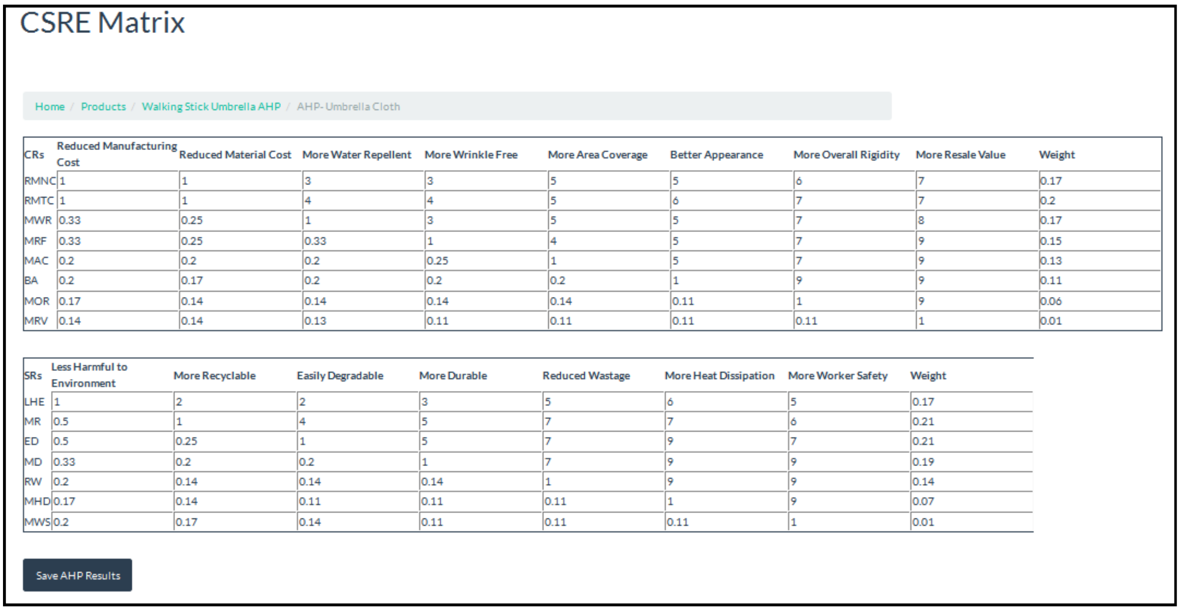


CSRE Matrix

AHP LINGUISTIC SCALE

Linguistic Scale	Importance Scale	Reciprocal Scale
Equal importance	1	1
Weak or slight	2	1/2
Moderate importance	3	1/3
Moderate plus	4	1/4
Strong importance	5	1/5
Strong plus	6	1/6
Very strong or demonstrated importance	7	1/7
Very , very strong	8	1/8
Extreme importance	9	1/9

Figure 7.18 CSREMDSS – AHP approach where drop down menu shows importance rating and linguistic scale.



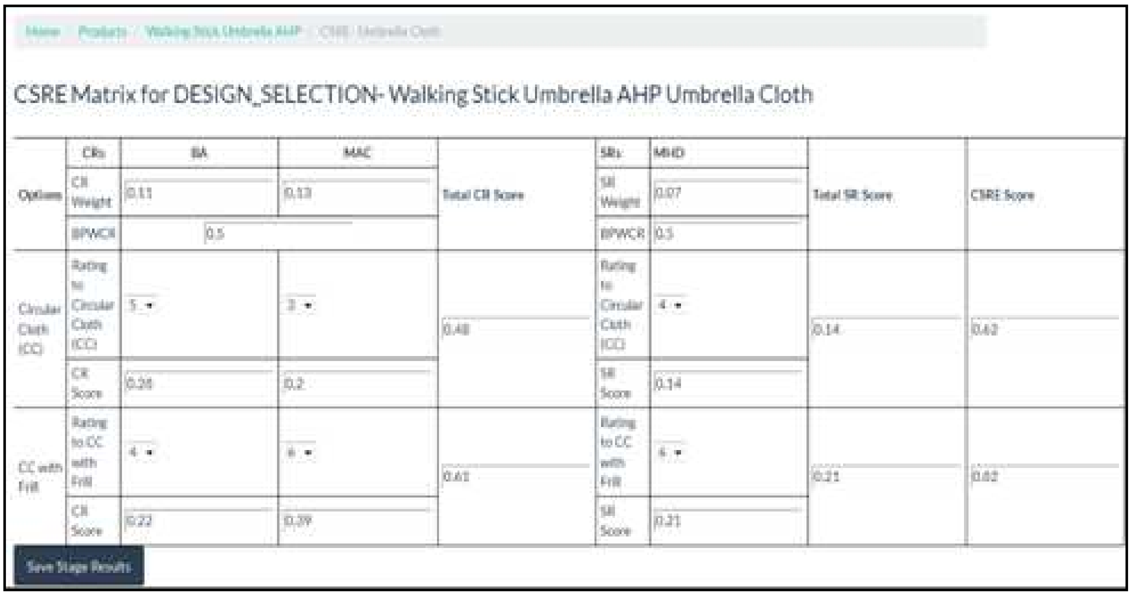
CSRE Matrix

CRs	Reduced Manufacturing Cost	Reduced Material Cost	More Water Repellent	More Wrinkle Free	More Area Coverage	Better Appearance	More Overall Rigidity	More Resale Value	Weight
RMNC	1	1	3	3	5	5	6	7	0.17
RMTC	1	1	4	4	5	6	7	7	0.2
MWR	0.33	0.25	1	3	5	5	7	8	0.17
MRF	0.33	0.25	0.33	1	4	5	7	9	0.15
MAC	0.2	0.2	0.2	0.25	1	5	7	9	0.13
BA	0.2	0.17	0.2	0.2	0.2	1	9	9	0.11
MOR	0.17	0.14	0.14	0.14	0.14	0.11	1	9	0.06
MRV	0.14	0.14	0.13	0.11	0.11	0.11	0.11	1	0.01

SRs	Less Harmful to Environment	More Recyclable	Easily Degradable	More Durable	Reduced Wastage	More Heat Dissipation	More Worker Safety	Weight
LHE	1	2	2	3	5	6	5	0.17
MR	0.5	1	4	5	7	7	6	0.21
ED	0.5	0.25	1	5	7	9	7	0.21
MD	0.33	0.2	0.2	1	7	9	9	0.19
RW	0.2	0.14	0.14	0.14	1	9	9	0.14
MHD	0.17	0.14	0.11	0.11	0.11	1	9	0.07
MWS	0.2	0.17	0.14	0.11	0.11	0.11	1	0.01

Figure 7.19 CSREMDSS – Screen shot showing CRs and SRs weights calculated using AHP method.

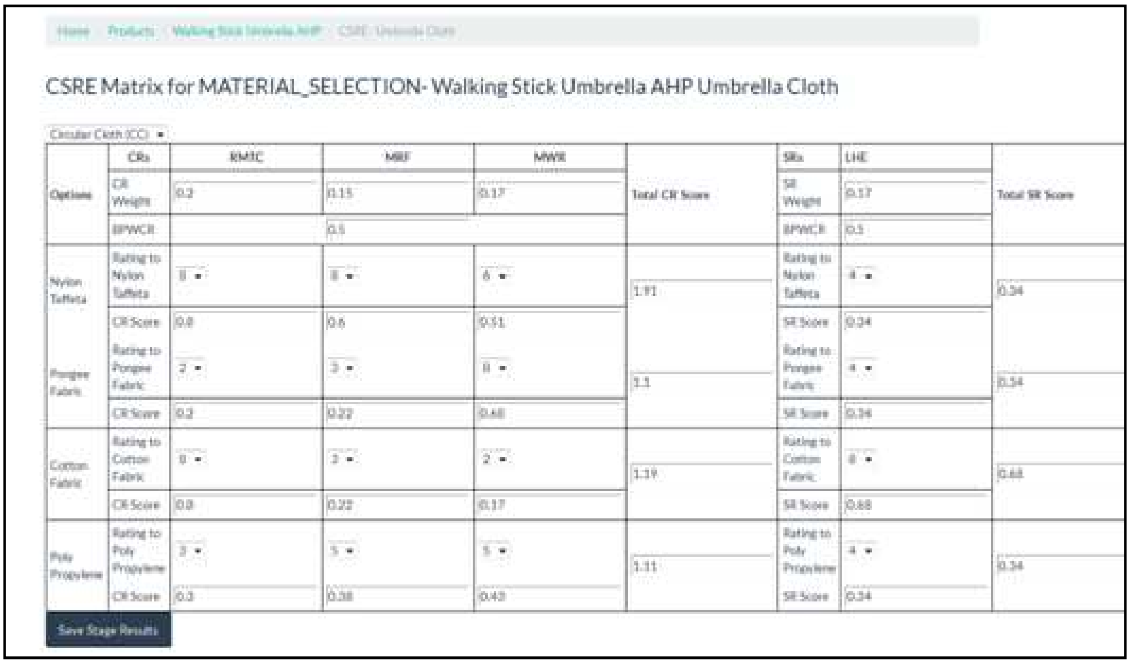
The CSRE Matrices corresponding to all the PDC stages were developed for the component umbrella cloth with the AHP method. Figures 7.20 to 7.24 depict CSRE Matrices of Design Selection, Material Selection, Manufacturing Process selection, Usage Selection and Disposal Selection respectively.



CSRE Matrix for DESIGN_SELECTION- Walking Stick Umbrella AHP Umbrella Cloth

Options	CRs	BA	MAC	Total CR Score	SRs	MHD	Total SR Score	CSRE Score
	CR Weight	0.11	0.13		SR Weight	0.07		
	BPWCR	0.5			BPWCR	0.5		
Circular Cloth (CC)	Rating to Circular Cloth (CC)	5	3	0.48	Rating to Circular Cloth (CC)	4	0.14	0.62
	CR Score	0.28	0.2		SR Score	0.14		
CC with Frill	Rating to CC with Frill	4	6	0.61	Rating to CC with Frill	6	0.21	0.82
	CR Score	0.22	0.39		SR Score	0.21		

Figure 7.20 CSREMDSS – DS Matrix using AHP approach

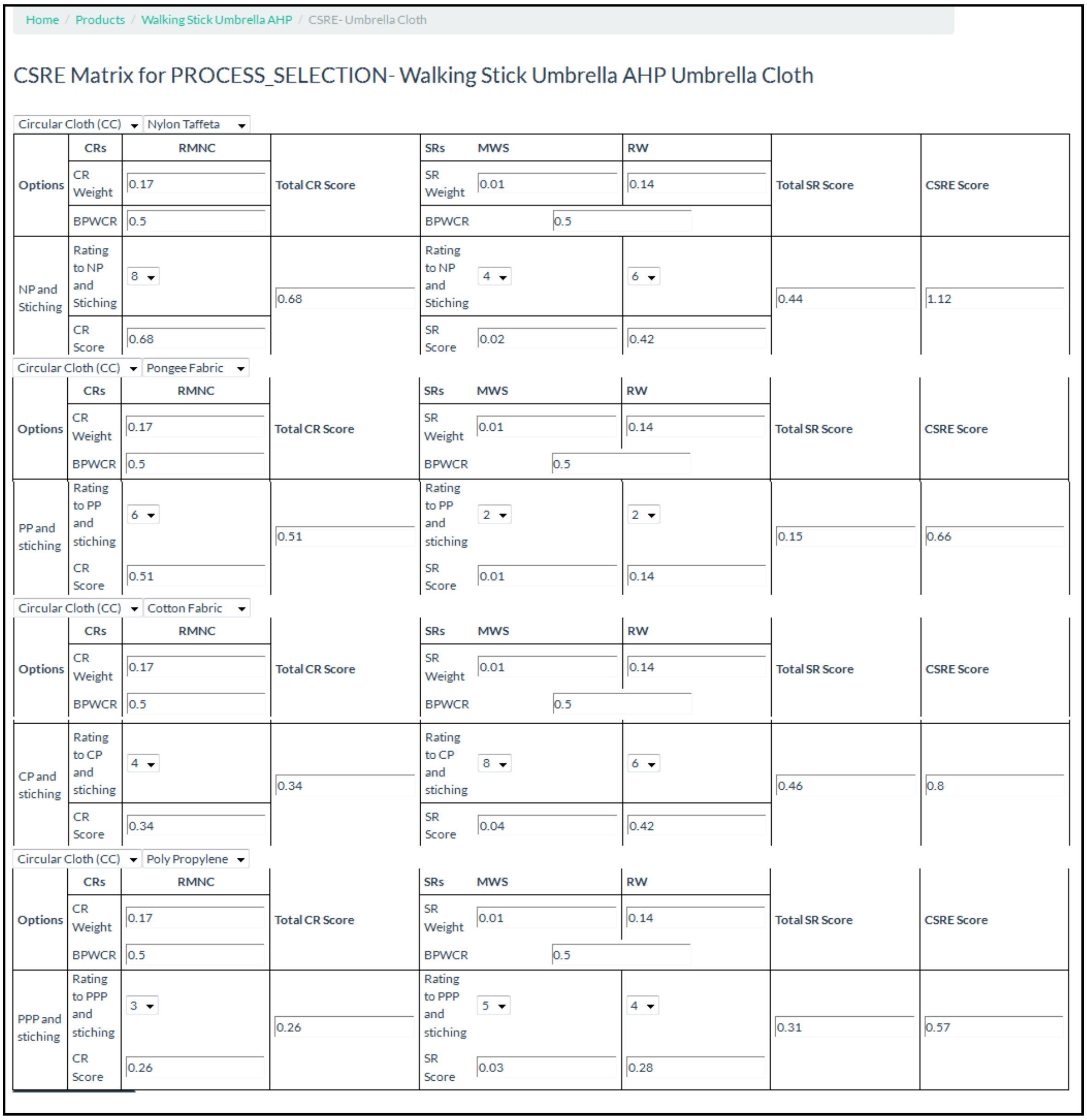


CSRE Matrix for MATERIAL_SELECTION- Walking Stick Umbrella AHP Umbrella Cloth

Circular Cloth (CC)

Options	CRs	RMTC	MRF	MWR	Total CR Score	SRs	LHE	Total SR Score
	CR Weight	0.2	0.15	0.17		SR Weight	0.17	
	BPWCR		0.5			BPWCR	0.5	
Nylon Taffeta	Rating to Nylon Taffeta	8	8	6	1.91	Rating to Nylon Taffeta	4	0.34
	CR Score	0.8	0.6	0.51		SR Score	0.34	
Pongee Fabric	Rating to Pongee Fabric	2	3	8	1.1	Rating to Pongee Fabric	4	0.34
	CR Score	0.2	0.22	0.68		SR Score	0.34	
Cotton Fabric	Rating to Cotton Fabric	8	3	2	1.19	Rating to Cotton Fabric	8	0.68
	CR Score	0.8	0.22	0.17		SR Score	0.68	
Poly Propylene	Rating to Poly Propylene	3	5	5	1.11	Rating to Poly Propylene	4	0.34
	CR Score	0.3	0.38	0.43		SR Score	0.34	

Figure 7.21 CSREMDSS – MS Matrix using AHP approach



Home / Products / Walking Stick Umbrella AHP / CSRE- Umbrella Cloth

CSRE Matrix for PROCESS_SELECTION- Walking Stick Umbrella AHP Umbrella Cloth

Circular Cloth (CC) ▾ Nylon Taffeta ▾

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.17		SR Weight	0.01	0.14		
	BPWCR	0.5		BPWCR	0.5			
NP and Stiching	Rating to NP and Stiching	8 ▾	0.68	Rating to NP and Stiching	4 ▾	6 ▾	0.44	1.12
	CR Score	0.68		SR Score	0.02	0.42		

Circular Cloth (CC) ▾ Pongee Fabric ▾

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.17		SR Weight	0.01	0.14		
	BPWCR	0.5		BPWCR	0.5			
PP and stiching	Rating to PP and stiching	6 ▾	0.51	Rating to PP and stiching	2 ▾	2 ▾	0.15	0.66
	CR Score	0.51		SR Score	0.01	0.14		

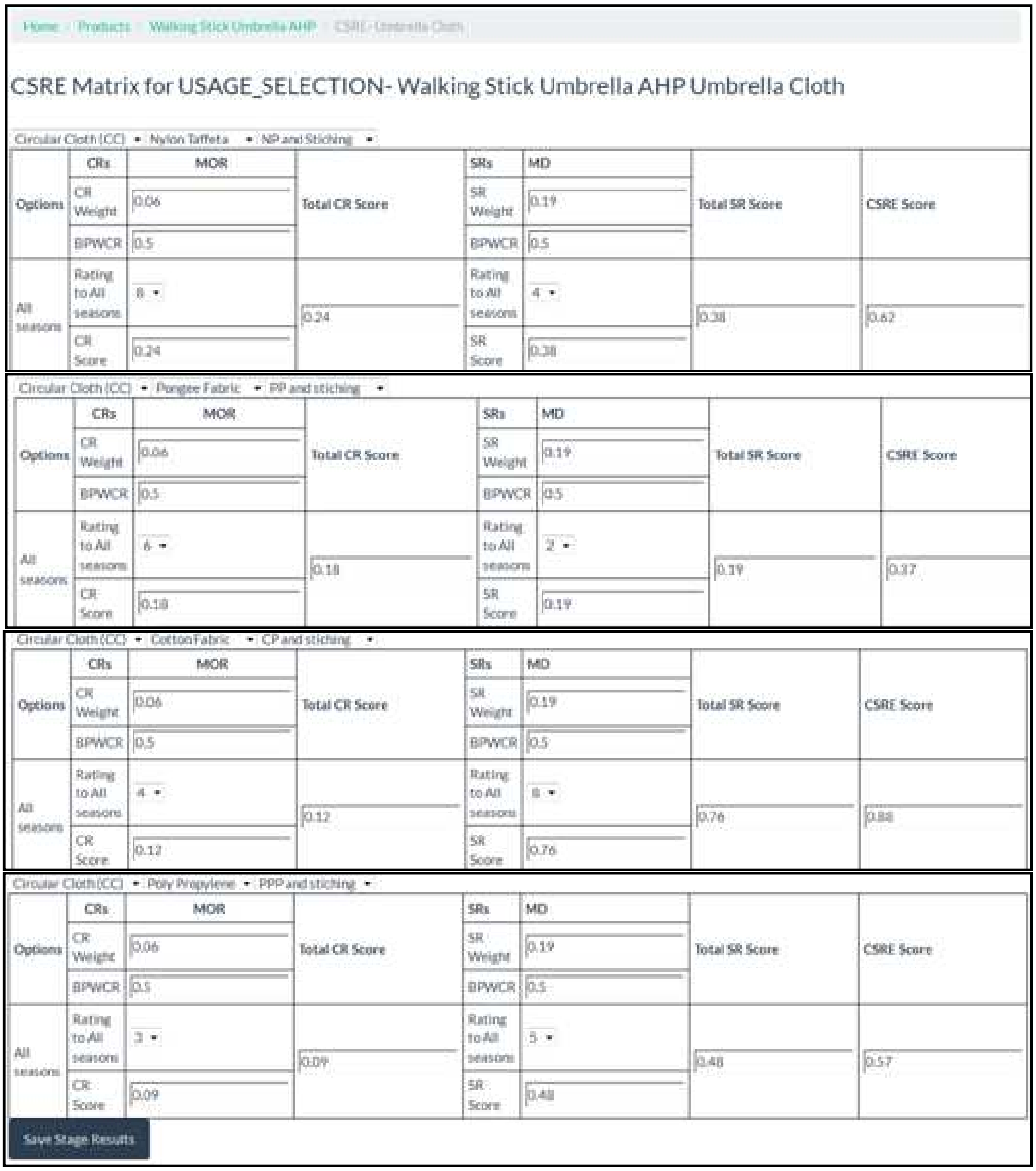
Circular Cloth (CC) ▾ Cotton Fabric ▾

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.17		SR Weight	0.01	0.14		
	BPWCR	0.5		BPWCR	0.5			
CP and stiching	Rating to CP and stiching	4 ▾	0.34	Rating to CP and stiching	8 ▾	6 ▾	0.46	0.8
	CR Score	0.34		SR Score	0.04	0.42		

Circular Cloth (CC) ▾ Poly Propylene ▾

Options	CRs	RMNC	Total CR Score	SRs	MWS	RW	Total SR Score	CSRE Score
	CR Weight	0.17		SR Weight	0.01	0.14		
	BPWCR	0.5		BPWCR	0.5			
PPP and stiching	Rating to PPP and stiching	3 ▾	0.26	Rating to PPP and stiching	5 ▾	4 ▾	0.31	0.57
	CR Score	0.26		SR Score	0.03	0.28		

Figure 7.22 CSREMDSS – MPS Matrix using AHP approach



CSRE Matrix for USAGE_SELECTION- Walking Stick Umbrella AHP Umbrella Cloth

Circular Cloth (CC) ▾ Nylon Taffeta ▾ NP and Stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.06		SR Weight	0.19		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	8 ▾	0.24	Rating to All seasons	4 ▾	0.38	0.62
	CR Score	0.24		SR Score	0.38		

Circular Cloth (CC) ▾ Pongee Fabric ▾ PP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.06		SR Weight	0.19		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	6 ▾	0.18	Rating to All seasons	2 ▾	0.19	0.37
	CR Score	0.18		SR Score	0.19		

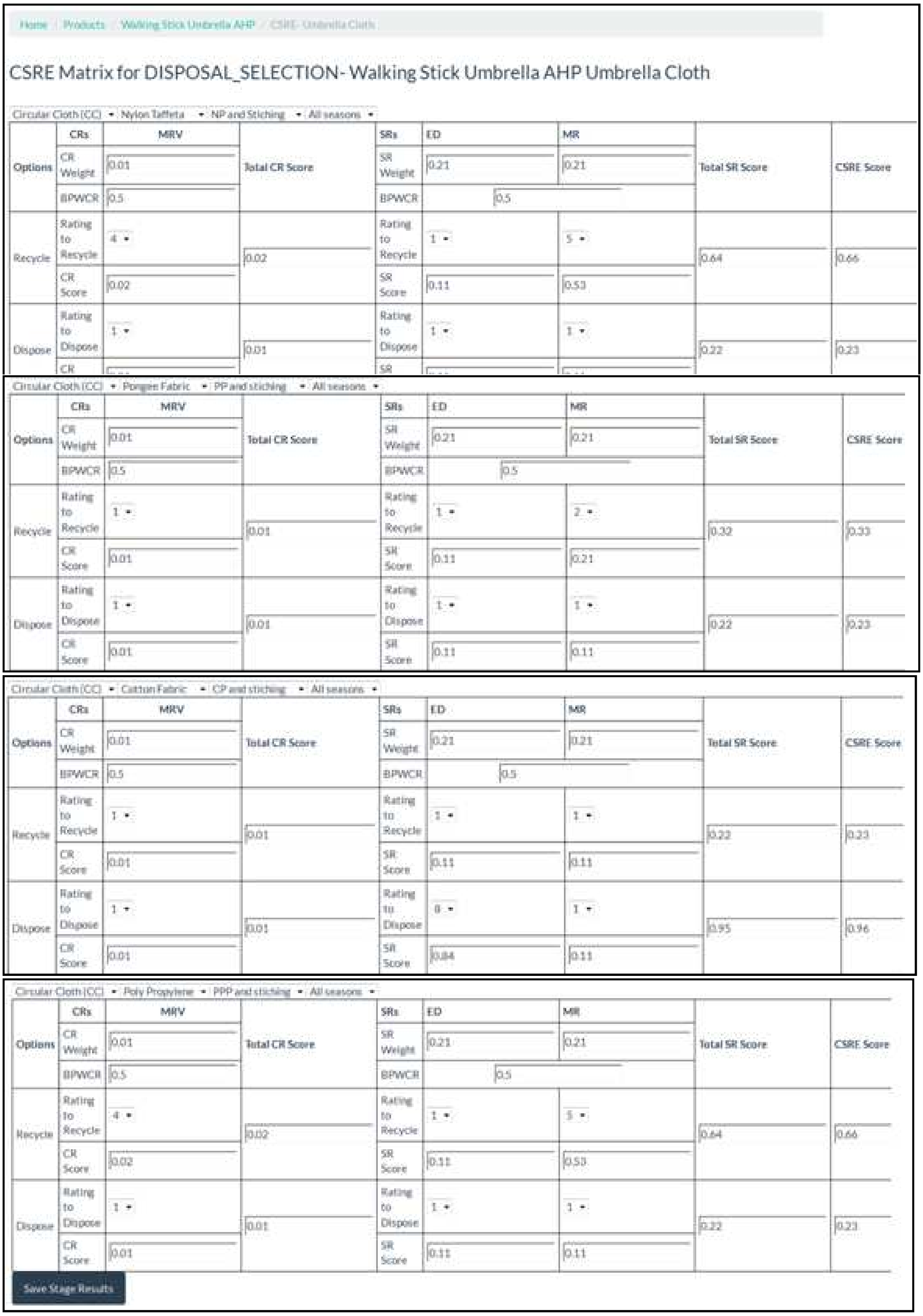
Circular Cloth (CC) ▾ Cotton Fabric ▾ CP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.06		SR Weight	0.19		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	4 ▾	0.12	Rating to All seasons	8 ▾	0.76	0.88
	CR Score	0.12		SR Score	0.76		

Circular Cloth (CC) ▾ Poly Propylene ▾ PPP and stiching ▾

Options	CRs	MOR	Total CR Score	SRs	MD	Total SR Score	CSRE Score
	CR Weight	0.06		SR Weight	0.19		
	BPWCR	0.5		BPWCR	0.5		
All seasons	Rating to All seasons	3 ▾	0.09	Rating to All seasons	5 ▾	0.48	0.57
	CR Score	0.09		SR Score	0.48		

Figure 7.23 CSREMDSS – US Matrix using AHP approach



Home / Products / Walking Stick Umbrella AHP / CSRE- Umbrella Cloth

CSRE Matrix for DISPOSAL_SELECTION- Walking Stick Umbrella AHP Umbrella Cloth

Circular Cloth (CC) ▾ Nylon Taffeta ▾ NP and Stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.01		SR Weight	0.21	0.21		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	4 ▾	0.02	Rating to Recycle	1 ▾	5 ▾	0.64	0.66
	CR Score	0.02		SR Score	0.11	0.53		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.22	0.23
	CR			SR				

Circular Cloth (CC) ▾ Pongee Fabric ▾ PP and stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.01		SR Weight	0.21	0.21		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	1 ▾	0.01	Rating to Recycle	1 ▾	2 ▾	0.32	0.33
	CR Score	0.01		SR Score	0.11	0.21		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.22	0.23
	CR Score	0.01		SR Score	0.11	0.11		

Circular Cloth (CC) ▾ Cotton Fabric ▾ CP and stiching ▾ All seasons ▾

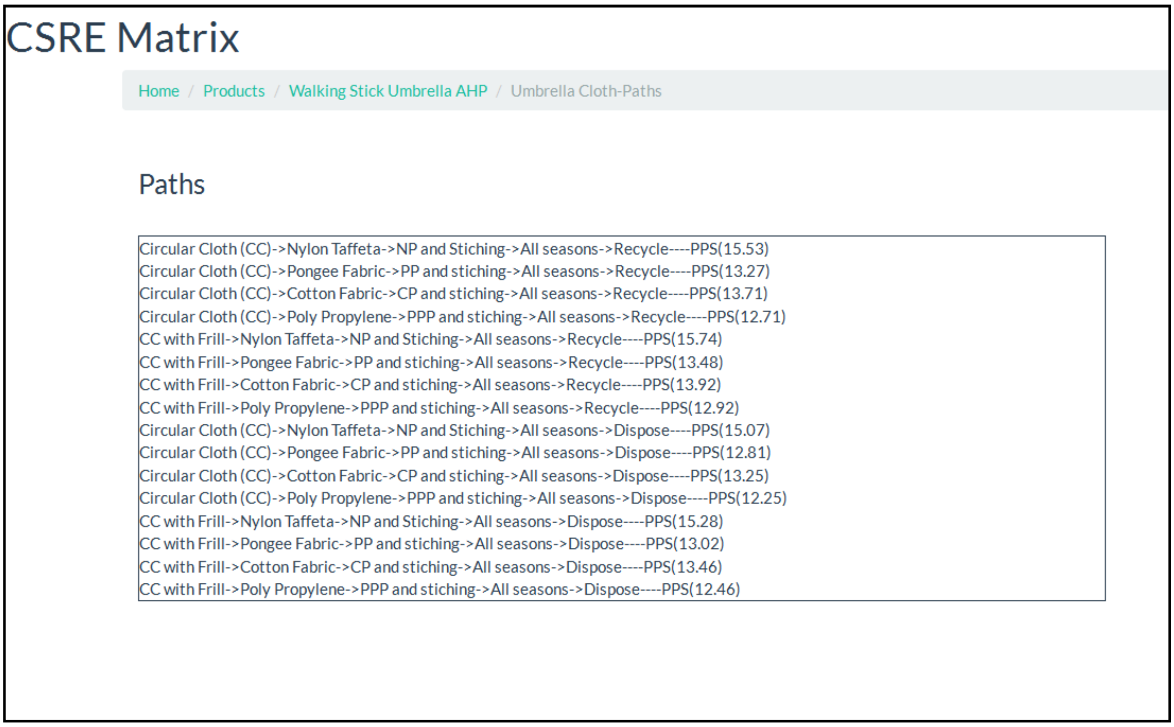
Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.01		SR Weight	0.21	0.21		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	1 ▾	0.01	Rating to Recycle	1 ▾	1 ▾	0.22	0.23
	CR Score	0.01		SR Score	0.11	0.11		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	8 ▾	1 ▾	0.95	0.96
	CR Score	0.01		SR Score	0.84	0.11		

Circular Cloth (CC) ▾ Poly Propylene ▾ PPP and stiching ▾ All seasons ▾

Options	CRs	MRV	Total CR Score	SRs	ED	MR	Total SR Score	CSRE Score
	CR Weight	0.01		SR Weight	0.21	0.21		
	BPWCR	0.5		BPWCR	0.5			
Recycle	Rating to Recycle	4 ▾	0.02	Rating to Recycle	1 ▾	5 ▾	0.64	0.66
	CR Score	0.02		SR Score	0.11	0.53		
Dispose	Rating to Dispose	1 ▾	0.01	Rating to Dispose	1 ▾	1 ▾	0.22	0.23
	CR Score	0.01		SR Score	0.11	0.11		

Figure 7.24 CSREMDSS – DiS Matrix using AHP approach

When AHP method was used, the weights to individual CRs and SRs were different from ROC method and the path scores also were different accordingly. The combination path, Circular Cloth with Frill as design, Nylon Taffeta as material, Nylon Production and Stitching as Manufacturing Process, All season as usage and Recycle as disposal got a maximum score of 15.74 as shown in Fig. 7.25. The second combination path score obtained was 15.53 against Circular Cloth as design and Nylon Taffeta as material, Nylon Production and Stitching as Manufacturing Process, All season as usage and Recycle as disposal. DrS stage was constructed separately.



```
Circular Cloth (CC)->Nylon Taffeta->NP and Stiching->All seasons->Recycle----PPS(15.53)
Circular Cloth (CC)->Pongee Fabric->PP and stiching->All seasons->Recycle----PPS(13.27)
Circular Cloth (CC)->Cotton Fabric->CP and stiching->All seasons->Recycle----PPS(13.71)
Circular Cloth (CC)->Poly Propylene->PPP and stiching->All seasons->Recycle----PPS(12.71)
CC with Frill->Nylon Taffeta->NP and Stiching->All seasons->Recycle----PPS(15.74)
CC with Frill->Pongee Fabric->PP and stiching->All seasons->Recycle----PPS(13.48)
CC with Frill->Cotton Fabric->CP and stiching->All seasons->Recycle----PPS(13.92)
CC with Frill->Poly Propylene->PPP and stiching->All seasons->Recycle----PPS(12.92)
Circular Cloth (CC)->Nylon Taffeta->NP and Stiching->All seasons->Dispose----PPS(15.07)
Circular Cloth (CC)->Pongee Fabric->PP and stiching->All seasons->Dispose----PPS(12.81)
Circular Cloth (CC)->Cotton Fabric->CP and stiching->All seasons->Dispose----PPS(13.25)
Circular Cloth (CC)->Poly Propylene->PPP and stiching->All seasons->Dispose----PPS(12.25)
CC with Frill->Nylon Taffeta->NP and Stiching->All seasons->Dispose----PPS(15.28)
CC with Frill->Pongee Fabric->PP and stiching->All seasons->Dispose----PPS(13.02)
CC with Frill->Cotton Fabric->CP and stiching->All seasons->Dispose----PPS(13.46)
CC with Frill->Poly Propylene->PPP and stiching->All seasons->Dispose----PPS(12.46)
```

Figure 7.25 CSREMDSS – Path with Path scores using AHP approach

7.4 RESULTS AND DISCUSSION

A Decision Support System is developed and put into practice for assisting practitioners in developing new sustainable product which satisfy the customers. The various steps of CSRE Matrix in each stage of the product development stages are developed using a decision support system. The DSS is explained with demonstrations of the use of the tool in an umbrella manufacturing company.

7.5 CHAPTER SUMMARY

The success of a product in the present competitive market depends on its prolonged presence in the maturity stage of the product life cycle. The CSREMDSS help the designer to arrive at various combination options in PDC stages for producing a customer satisfying sustainable product quickly and thereby reduce time to market. CSRE Matrices of each PDC stage can be built using CSREMDSS and thus NPD become an easy task in front of the designers. In addition, CSREMDSS is carried out as a systematic approach where complex data analysis and computations in multi-decision support tools are handled by the system.

CHAPTER 8

CONCLUSION

8.1 PREAMBLE

Accomplishing present generation’s needs without compromising the needs of the future generations can only be achieved through the cautious extraction and use of resources. Sustainable product development has a significant role in reaching this level of sustainability. Organizations are now increasingly conscious about sustainable product development and they are badly in need of sustainable product development tools to design and manufacture their products.

Traditional new product development tools were mainly concentrating on cost/profit models that would increase their bottom line (Kaebernick et al., 2003). Modern day business strategies take advantage of the new product development methods to achieve reduced cost and improved quality of the products (Liu et al., 2010). In addition to cost and quality, introduction of environmental requirements into design has also emerged as a new competitive strategy (Koltun, 2010).

Life Cycle Assessment (LCA) is one of such widely accepted approach for evaluating environmental and economic impacts of a product, process or an activity (Roy et al., 2009). Apart from environmental and economic aspects, social aspects as a third dimension of sustainability need to be reckoned for the evaluation of sustainability level. Many researchers have attempted to integrate LCA with other tools such as Quality

Function Deployment, TRIZ etc. These attempts supplemented the acceptance level of LCA as an assessment/new product development tool. However, these attempts cannot avoid or reduce the adverse effect of product's cost escalation due to the introduction of environmental requirements into new product development (Kaebernick et al., 2003).

The necessity of a paradigm shift in new product development tools has resulted in a cost, profit, quality, and sustainable model that reckon voice of customers, voice of environment, voice of society and voice of manufacturers. Optimization of all these requirements using a sustainable product development tool is the main challenge encountered by the designers.

During systematic literature review, it was noticed that very few works were reported related to the construction of sustainable product development tools. In addition, the tools and methods that consider an integrated approach of all the three dimensions of sustainable development are quite a few. The literature review conducted for this research works emphasized the importance of integrating all the three dimensions of sustainable development in new product development. It was also noticed that the existing tools that consider all the three dimensions of sustainability do not separately weigh sustainability requirements and customer requirements. This may reduce the importance of sustainability requirements over customer requirements. Some other tools that consider all the three dimensions of sustainability do not weigh its elements and sub-elements.

Sustainable product development tools are not generally distinguished from sustainability assessment tools in literature. Nevertheless, there is a fundamental difference between these two types in its application arena. Product assessment tools evaluate sustainability impact of the product; whereas product development tools try to avoid impact on sustainability. Even though enormous numbers of tools have been developed for sustainability assessment, there is still lack of tools for sustainable product development. The tools that consider environmental aspects in product development do not have a general perspective on sustainability to encompass other two dimensions of sustainability namely social and economic.

8.2 RESEARCH DELIVERABLES

A new tool namely CSRE Matrix has been developed as part of the research work. The primary objective was to develop a tool that incorporates sustainability requirements and customer requirements into new product development. Most of the existing new product development tools merely focus on achieving customer satisfaction. Literature review revealed that a very few number of tools have been developed for sustainable new product development which considers all the three dimensions of the sustainability along with customer requirements. CSRE Matrix proposed in this doctoral work reckons all the three dimensions of sustainable development along with customer requirements.

CSRE matrix weighs CRs and SRs separately to evaluate different options in each stage of product development cycle based on the fulfillment level of CRs and SRs. The importance of both CRs and SRs were not reduced due to the priority of the other. When CRs are considered as part of SRs, CRs may be weighed more to SRs, as it is the prime objective of new product development. CSRE Matrix overcomes this limitation by weighing CRs and SRs separately while computing the scores of different alternatives. In addition, CSRE Matrix introduces business policy weight to CRs and SRs as a new concept. By including business policy weights, companies can take policies either to support CRs or

SRs. In addition, each alternative at product development stages is rated based on its fulfillment to voice of customers and voice of sustainability.

Case studies were conducted in three different industries for testing the acceptability and applicability of the CSRE Matrix. Evaluations of different options at different stages of the product development have been carried out for the products namely 500 ml edible oil bottle, 750 ml ayurvedic medicine bottle and for walking stick umbrella. The best options under each stage of product development could be determined easily and the same was unanimously agreed by the practitioners involved in the studies.

The personnel who participated in the case studies supported the proposed tool and expressed their opinion that it can be used effectively in their organization for the development of sustainable and customer satisfying products. They also agreed that the proposed tool assess alternative options in PDC stages based on customer requirements and sustainability requirements of products considered. In short, the case study suggested that CSRE Matrix can be used effectively as a new product development tool that focuses on sustainable product development without compromising customer satisfaction.

The calculations and presentation of the CSRE matrix being time consuming, a decision support system named CSREMDSS was developed and used to facilitate the easy use of the proposed tool. Decision support system developed as part of this doctoral work helped the designers to construct CSRE Matrices with less effort. It was noticed that computations based on decision support tools such as AHP and ROC methods could easily be handled through this decision support system.

8.3 CHAPTER SUMMARY

The main objective of this thesis work was to construct a tool for product development that overcomes all the limitations of the existing sustainable product development tools. By introducing CSRE Matrix, this research work has attempted to fulfill its objectives and has been succeeded.

CSRE Matrix has reckoned customer requirements and sustainability requirements separately and hence do not allow customer requirements dominating over sustainability requirements. CSRE Matrix considers all the three dimensions of sustainability namely environmental, social and economic. In order to include all the sub-elements of sustainability requirements under the three dimensions of sustainability, brainstorming technique has been applied among design team members. This approach helped them to obtain broad picture of all the sustainability requirements and prioritize the sub-elements of a particular sustainability dimension which has predominance over the other. Case studies conducted on the development of three products in two industries corroborated the usefulness and acceptability of the proposed tool.

The decision support system ‘CSREMDSS’ developed as a part of this thesis works was aimed to reduce the difficulties in the construction of CSRE Matrices and to simplify the calculations involved. CSREMDSS also helps in structuring CSRE Matrices of each stages of product development cycle very accurately and quickly.

In developing the proposed tool ‘CSRE Matrix’, the aim was to construct a relatively simple and easily buildable tool for sustainable new product development. CSRE

Matrix in its present form has tried to serve this purpose and the endeavor has fulfilled its responsibilities towards a sustainable future.

8.4 LIMITATIONS OF THE RESEARCH WORK

The following limitations were observed during design of the CSRE matrix and the implementation studies.

CSRE Matrix is developed based on the qualitative information from the experts involved. Hence, the selection of design team members must be based on their overall knowledge in design and sustainability aspects. Availability of personnel having knowledge in manufacturing of the products and the sustainability aspects of the design and processes is important for the organizations to reap benefits of this tool.

The weighing of CRs and SRs as a whole is possible in the CSRE Matrix. This feature can be used to decide the fulfillment of CRs and SRs. The top management of the organization can decide this weight. This has to be done carefully, since providing more weights of CRs and less weight to SRs can convert the product into a customer satisfying product than a customer satisfying sustainable product.

The CSRE Matrix considers different possible alternatives in the different stages of its product life cycle. The designer has to check the compatibility of these alternatives carefully. Compatibility checking of products with more components and subcomponents needs designer’s special attention. However, once the designer is more used with the tool and follows an approach that considers the best options in each stage of the product development cycle, the difficulty of selecting the best option can be minimized.

8.5 SCOPE FOR FUTURE RESEARCH

CSRE Matrix has been constructed as a generic tool which can be used for the development of any type of products. It is more effective in the case of new product development where quantitative information is not available for designers. In the case of product development that focus on modification of existing product, where quantitative information are available, qualitative assessment by comparing physical parameters of each option quantitatively would help in making better decisions. LCA of an existing product can offer more information for comparing physical parameters. Integration of decision support system of CSRE Matrix with any one of the LCA decision support system is one of the possible future scopes of works in this regard.

CSRE Matrix was test implemented in very few manufacturing organizations. Inferences from the study revealed that it can be used in many other manufacturing organizations. For this purpose, if a database of common sustainability requirements and customer requirements is available for similar products, CSRE Matrix can be used more effectively in any type of industries.

According to Ziout et al., 2013, significance level of each of the three sustainability dimensions is not equal. In order to widen the scope of the CSRE Matrix, the importance to individual dimensions of sustainability can be weighed and considered which will benefit the prospective users.

While developing the decision support system of CSRE Matrix, fuzzy analytic hierarchy process (FAHP) method was not considered due to the cumbersome work involved in formulating the FAHP procedure in software programming. However, the addition of FAHP method in the DSS of CSRE Matrix would make it perfect.

The aforesaid modifications to the proposed CSRE Matrix shall benefit in a long term perspective. Moreover, radical innovations are required for CSRE Matrix for its global acceptance as a perfect new product development tool.

REFERENCES

1. Abdalla, T., Farhat, A., Diabat, A., Kennedy, S., 2012. Green supply chains with carbon trading and environmental sourcing: Formulation and life cycle assessment. Applied Mechanical Modelling 36 (9), 4271-4285.
2. Ahmed, M.D., Sundaram, D., 2012. Sustainability modeling and reporting: From road map to implementation, Decision Support System 53, 611-624.
3. Ahn, B.S., 2011. Compatible weighting method with rank order centroid: Maximum entropy ordered weighted averaging approach. European Journal of Operation Research 212, 552-559.
4. Akao, Y., 1990. Quality Function Deployment: Integrating Customer Requirements into Product Design. Productivity Press, Cambridge, MA.
5. Alemam,A., Li, S., 2014. Integration of Quality Function Deployment and Functional Analysis for Eco-design. International Journal of Mechanical Engineering and Mechatronics 2 (1), 1-9.
6. Ali, A.J., Islam, Md.A., Howe,L.P., 2012. A study of sustainability of continuous improvement in the manufacturing industries in Malaysia Organizational self-assessment as a mediator, Management of Environmental Quality: An International Journal 24 (3), 408-426.
7. Allenby, B.R., 2000. Implementation industrial ecology: The AT&T matrix system. Interfaces 30 (3), 42-54.
8. Allione, C., Giorgi, C.D., Lerma, B., Petruccelli, L., 2012. From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multi criteria environmental profile of a material. Energy 39, 90-99.
9. Ardente, F., Beccali, G., Cellura, M., Brano, V.L., 2005. Life cycle assessment of solar thermal collector. Renewable Energy 30, 1031-1054.
10. Armacost, R.L, Componation, P.J, Mullens, M.A, Swart, W.S., 1994. An AHP framework for prioritizing customer requirements in QFD: An industrial housing application. IIE Transactions 26, (4), 72-79.
11. Asamoah, D., Annan, J., Nyarko, S., 2012. AHP approach for Supplier Evaluation and Selection in a Pharmaceutical Manufacturing Firm in China. International Journal of Business Management 7 (10), 49-62.
12. Aurich, J.C., Linke, B., Hauschild,M., Carrella,M., Kirsch,B., 2013. Sustainability of abrasive processes. CIRP Annals – Manufacturing Technology 62, 653-672.
13. Azapagic, A., 2004. Developing a framework for sustainable development indicators for the mining and minerals industry, Journal of Cleaner Production 12 (6), 639-662.
14. Azapagic, A., Perdan, S., 2000. Indicators of sustainable development for industry: a general frame work. Process Safety and Environmental Protection, Institution of Chemical Engineers 78 (4), 243-261.

15. Barron, F.H., Barret, B.E., 1996. Decision quality using ranked attribute weights. Management Science 42, 1515–1523.

16. Baumann H, Boons F, Bragd A., 2002. Mapping green product developmentfield: engineering, policy, and business perspective. Journal of Cleaner Production 10, 9-25.

17. Besharati, B., Azarm, S., Kannan, P.K., 2006. A decision support system for product design selection:A generalized purchase modeling approach, Decision Support Systems 42, 333– 350.

18. Besterfield, D.H., Besterfield-Michna, C., Besterfield, G.H., Besterfield-Sacre, M., 2004. Total Quality Management. Pearson Education, India.

19. Bhattacharya, A., Sarkar, B., Mukherjee, S.K., 2005. Integration of AHP with QFD for robot selection under requirement perspective. International Journal of Production Research 43 (17), 3671-3685.

20. Biju, P.L., Shalij, P.R., Prabhushankar, G.V., 2015. Evaluation of customer requirements and sustainability requirements through fuzzy analytic Hierarchy process. Journal of Cleaner Production 108, 808-817.

21. Bottani, E., Rizzi, A., 2006. Strategic management of logistics service: A fuzzy QFD approach. International Journal of production economics 103, 585-599.

22. Bowea, D., Wang, B., 2003. Identifying environmental improvement options by combining life cycle assessment and fuzzy set theory. International Journal of production Research 41(3), 593-609.

23. Brezet H., Van Hamel, C., 1997. Eco design: a promising approach to sustainable production and consumption. Delft University of Technology. United Nations Environment Programme (UNEP). The Netherlands.

24. Brundtland, G. (Ed.), 1987. Our Common Future: The World Commission on Environment and Development. Oxford University Press, Oxford.

25. Burke, S., Gaughran, W.F., 2007. Developing a framework for sustainability management in engineering SMEs. Robotics and Computer-Integrated Manufacturing 23 (6), 696-703.

26. Byggeth, S., Broman, G., Robert, K-H., 2007. A method for sustainable product development based on a modular system of guiding questions. Journal of Cleaner Production 15 (1), 1-11.

27. Byggeth, S., Hochschorner, E., 2006. Handling trade-offs in Eco design tools for sustainable product development and procurement. Journal of Cleaner Production 14, 1420-1430.

28. Carvalho, A., Matos, H.A., Gani, R., 2013. SustainPro – A tool for systematic process analysis, generation and evaluation of sustainable design alternatives. Computers and Chem. Engineering 50, 8-37.

29. Celik, M., Deha Er, I., Ozok,A.F., 2009. Application of fuzzy extended AHP methodology on shipping registry selection: The case of Turkish maritime industry. Expert System with Application 36, 8190-198.

30. Chan, S.L., Ip, W.H., 2011. A dynamic decision support system to predict the value of customer for new product development. Decision Support Systems 52, 178-188.

31. Chang, D.-Y., 1996. Applications of the extent analysis method on fuzzy AHP. European Journal of Operational Research 95, 649-655.

32. Charter, M.C., Belmane., 1999. Integrated Product Policy (IPP) and eco-product development (EPD). The Journal of Sustainable Product Design 10, 17-29.

33. Chiu, M-C., Chu, C-H., 2012. Review of Sustainable Product design from Life Cycle Perspectives. International journal of precision engineering and manufacturing 13 (7), 1259-1272.

34. Choi, S.H., Ahn, B.S., 2011. Rank order based recommendation approach for multiple featured products. Expert Syst. with Applications 38, 7081-7087.

35. Clancy, G., Fröling, M., Svanström, M., 2013. Changing from petroleum to wood-based materials: critical review of how product sustainability characteristics can be assessed and compared. Journal of Cleaner Production 39, 372-385.

36. Dehghanian, F., Mansour, S., 2009. Designing sustainable recovery network of end-of-life products using genetic algorithm. Resources, Conservation and Recycling, 53, 559-570.

37. Despeisse, M., Mbaye, F., Ball, P.D., Levers, A., 2012. The emergence of sustainable manufacturing practices. Production Planning & Control: The Management of Operations 23 (5), 354-376.

38. Dikmen, I., Birgonul, M.T., Kiziltas, S., 2005. Strategic use of quality function deployment (QFD) in the construction industry. Building and Environment 40, 245–255.

39. Eagan P, Weinberg L., 1997. Development of a streamlined, life-cycle, design for the environment (DFE) tool for manufacturing process modification: a Boeing Defense and Space Group case study. In: Proceedings of the 1997 IEEE international symposium on electronics and the environment, pp. 188–891.

40. Elkington, J., 1998. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. New Society Publishers, Gabriola Island, BC Canada.

41. Fargnoli, M., Sakao, T., 2008. Coordinating Ecodesign Methods in Early Stages of Industrial Product Design. Int. J. Environmentally Conscious Design & Manufacturing 14 (2), 35-65.

42. Gaha, R., Yannou, B., Benamara, A., 2014. A new eco-design approach on CAD systems. International Journal of Precisiion Engineering and Manufacturing 15, 1443-1451.

43. García-Serna, J., Pérez-Barrigón, L., Cocero, M.J., 2007. New trends for design towards sustainability in chemical engineering: Green engineering. Chemical Engineering Journal 133, 7-30.

44. Ghadimi, P., Azadnia, A.H., Yusof, N.H., Saman, M.Z.M., 2012. A weighted fuzzy approach for product sustainability assessment: a case study in automotive industry. Journal of cleaner Production 33, 10-21.

45. Gomes, C.M., Kneipp, J.M., Kruglianskas, I., Rosa, L.A.B., Bichueti, R.S., 2014. Management for sustainability in companies of the mining sector: an analysis of the main factors related with the business performance. Journal of Cleaner Production 84, 84-93.

46. Graedel TE, Allenby B R., 1995. Industrial Ecology. New Jersey. Prentice Hall.

47. Greenberg, A., Quillian, L., 2012. Managing Sustainable Production: A Framework for integrating sustainability in manufacturing, Environmental Quality Management, pp. 29-41.Wileyonlinelibrary.com. DOI: 10.1002/tqem.21305.

48. Gungor, A., Guptha, S.M., 1999. Issues in environmentally conscious manufacturing and product recovery: a survey. Computers and Industrial Engineering 36, 811-853.

49. Haes, H.A.U., Heijungs, R., 2007. Life-cycle assessment for energy analysis and management. Applied Energy 84, 817-827.

50. Hanumaiah, N., Ravi, B., Mukherjee, N.P., 2006. Rapid hard tooling process selection using QFD-AHP methodology. Journal of Manufacturing Technology Management 17 (3), 332-350.

51. Hassan, M.F., Saman, M.Z.M., Sharif, S., Omar, B., 2012. An Integrated MA-AHP approach for selecting the highest sustainability index of a new product. Procedia Social & Behavioral Science 57, 236-242.

52. Hauschild, M.Z., Dreyer, C., Jørgensen, A., 2008. Assessing social impacts in a life cycle perspective—Lessons learned, CIRP Annals - Manufacturing Technology 57, 21-24.

53. Heijungs, R., Huppes, G., Guinee, J.B., 2010. Life cycle assessment and sustainability analysis of products, materials and technologies towards a scientific framework for sustainability life cycle analysis. Polymer Degradation and Stability 95 (3), 422-428.

54. Hermann, B.G., Kroeze, C., Jawjit, W., 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. Journal of Cleaner Production 15, 1787-1796.

55. Hochschorner, E., Finnveden, G., 2003. Evaluation of Two Simplified Life Cycle Assessment Methods. International Journal of Life Cycle Assessment 8 (3), 119-128.

56. Hsiao, S-W., 2002. Concurrent design method for developing a new product. International Journal of Industrial Ergonomics 29 (1), 41-55.

57. Hu, G., Bidnda, B., 2009. Modeling sustainable product life cycle decision support system. International Journal of Production Economics, 122, 366-275.

58. Hutchins, M.J., Robinson, S.L., Dornfeld, D., 2013. Understanding life cycle social impacts in manufacturing: A processed-based approach. Journal of manufacturing systems 32, 536-542.

59. Jaafar, I.H., Venkatachalam, A., Joshi, K., Ungureanu, A.C., De Silva, N., Dillon Jr O.W., Rouch, K.E., Jawahir, I.S., 2007. Product Design for Sustainability: A New

Assessment Methodology and Case Studies, in Kutz M, (Ed.) Handbook of Environmentally Conscious Mechanical Design. John Wiley & Sons, pp. 25–65.

60. Jayal, A.D., Badurdeen, F., Dillon Jr, O.W., Jawahir, I.S., 2010. Sustainable Manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology 2, 144-152.

61. Jones, P., Comfort, D., Hillier, D., 2011. Sustainability in the Global Shop Window. International Journal of Retail and Distribution Management 39 (4), 256-271.

62. Jovane, F., Yoshikawa, H., Alting, L., Boer, C.R., Westkamper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M., 2008. The incoming global technological and industrial revolution towards competitive sustainable manufacturing. CIRP Annals – Manufacturing Technology 57, 641-659.

63. Jungbluth, N., Büsser, S., Frischknecht, R., Flury, K., Stucki. M., 2012. Feasibility of environmental product information based on life cycle thinking and recommendations for Switzerland. Journal of Cleaner Production 28, 187-197.

64. Kaebernick, H., Anityasari, M., Kara, S., 2002. Technical and economic model for end-of-life (EOL) options of industrial products. International Journal of environmental Sustainable Development 1 (2), 171–183.

65. Kaebernick, H., Kara, S., Sun, M., 2003. Sustainable product development and manufacturing by considering environmental requirements. Robotics and Computer Integrated Manufacturing 19, 461–468.

66. Kahraman, C., Cebeci, U., Ruan, D., 2004. Multi-attribute comparison of catering service companies using fuzzy AHP: The case of Turkey. International Journal of Production Economics 87, 171-184.

67. Karsak, E.E., Sozer, S., Alptekin, S.E., 2002. Product planning in quality function deployment using a combined analytic network process and goal programming approach. Computers and Industrial Engineering 44, 171-190.

68. Kasarda, M. E., Terpenny, J. P., Inman, D., Precoda, K. R., Jelesko, J., Sahin, A., Park, J., 2007. Design for adaptability (DFAD)—a new concept for achieving. Robotics and computer integrated manufacturing 23, 727-734.

69. Keoleian, G. A, Menerey, D., 1994. Sustainable Development by Design: Review of Life Cycle Design and Related Approaches. Journal of the Air and Waste Management Association 44, 645-668.

70. Khakee,A., 1999. Participatory scenarios for sustainable development. The journal of future studies, strategic thinking and policy 1 (3), 229-241.

71. Khan, F. I., Sadiq, R., Veitch, B., 2004. Life cycle index (LinX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production 12, 59–76.

72. Koltun, P., 2010. Materials and Sustainable Development. Progress in Natural Science: Materials International 20, 16-29.

73. Kuik, S.S., Nagalingam, S.V., Amer, Y., 2011. Sustainable supply chain for collaborative manufacturing. Journal of Manufacturing Technology and Management 23, 984-1001.

74. Kuo, T.C., Wu, H.H., Shieh, J.I., 2009. Integration of environmental considerations in quality function deployment by using fuzzy logic. Expert Systems with Applications 36 (3), 7146-7156.

75. Kwong, C.K., Bai, H., 2002. A fuzzy AHP approach to the determination of importance weights of customer requirements in quality function deployment. Journal of Intelligent Manufacturing 13, 367-377.

76. Lagerstedt, J., 2003. Functional and environmental factors in early phases of product development. Eco - Functional Matrix. Retrieved on 12/2/2014, http://www.dissertations.se/dissertation /72784b8768.

77. Lal, P., Janaki R. R., Alavalapati ., Marinescu, M., Matta, J.R., Dwivedi, P., Susaeta, A., 2011. Developing Sustainability Indicators for Woody Biomass Harvesting in the United States. Journal of Sustainable Forestry 30, 736-755.

78. Larsson, C.E., Martinsen, K., 2010. Requirements Engineering of Sustainable Manufacturing Performance Measurements. IMS2020 - Proceedings from the IMS2020 Summer School on Sustainable Manufacturing, pp. 122-132. Retrieved on 24/1/2013, http://www.detgarbra.no/publish/fil/vis/393.

79. Leal-Yepes, A. M., 2013. Evaluating the Effectiveness of Design for the Environment Tools to Help Meet Sustainability and Design Goals. Thesis. Rochester Institute of Technology.

80. Leopold, L.B., Clarke, F.E., Hanshaw, B.B., Balsley, J.R., 1971. United States Department of the Interior, Geological Survey Circular 645.

81. Li, J., Zeng, X., Stevels, A., 2014. Ecodesign in Consumer Electronics: Past, Present and Future. Critical Reviews in Environmental Science and Technologies 45, 840-860.

82. Liu, J., Wang, R., Yang, J., Shi, Y., 2010. The relationship between consumption and production system and its implications for sustainable development of China. Ecological Complexity 7 (2), 212-216.

83. Ljungberg, L.Y., 2007. Materials selection and design for development of sustainable products. Materials & Design 28 (2), 466–479.

84. Masui, K., Sakao, T., Kobayashi, M., Inaba, A., 2003. Applying Quality Function Deployment to Environmentally Conscious Design. International Journal of Quality and Reliability Management 20, 90-106.

85. Meadows, D., Meadows, D. (eds.), 1972. The Limits to Growth. A Report for the Club of Rome’s Project on the Predicament of Mankind. Universe Publications.

86. Miller, H.H., Russel, S.N., 2011. The adoption of sustainable Manufacturing Practices in the Carribbean. Business Strategy and Environment 20 (8), 512-528.

87. Moskowitz, H., Kim, K.J., 1997. QFD optimizer: a novice friendly quality function deployment decision support system for optimizing product designs. Computers & Industrial Engineering 32 (3), 641–655.

88. Nejati, M., Md. Shahbudin, A.S.B., Amran, A.B., 2010. Sustainable Development: a competitive advantage or a threat. Business Strategy Series 11(2), 84-89.

89. Noh J., Lee M. L., 2003. Application of Multi attribute Decision-making Methods for the Determination of Relative Significance Factor of Impact Categories. Environmental Management 31 (5), 633–641.

90. O'Brien, C., 2002. Global manufacturing and the sustainable economy. International Journal of Production Research 40 (5), 3867-3877.

91. Osborn, A., 1957. Applied imagination. Scribners, New York.

92. Pham, D.T., Thomas, A.J., 2012. Fit manufacturing: a framework for sustainability. Journal of Manufacturing Technology Management 23 (1), 103-123.

93. Pigosso, D.C.A., Sousa, S.R., 2011. Life Cycle Assessment (LCA): Discussion on Full-Scale and Simplified Assessment to Support the Product Development Process. 3rd international workshop advances in cleaner production. Psychology 15, 57-68.

94. Poel, I., 2007. Methodological problems in QFD and directions for future development. Research in Engineering Design 18 (1), 21-36.

95. Pusporini, P., Abhay, L., Luong, L., 2013. Integrating Environmental Requirements into Quality Function Deployment for Designing Eco-Friendly Product. International Journal of Materials, Mechanics and Manufacturing 1 (10, 80-84.

96. Ramani, K., Ramanujan, D., Bernstien, W-Z., Zao, F., Sutherland, Z., Handwerker , C., Choi, J-K., Kim, H., Thurston, D., 2010. Integrated Sustainable Life Cycle Design: A Review. Journal of Mechanical Design 132 (9), 1-15.

97. Ranganathan, J. Sustainability Rulers: Measuring Corporate Environmental and Social Performance. Sustainable Enterprise Perspectives, World Resource Institute: Washington, DC, 1998. Retrieved on 13/32014. http://www.wri.org/meb/pdf/janet/pdf.

98. Rayman-Bacchus, L., He, Z., 2014. Assessing clustered SME practice towards environmental and social impact: a Bourdiesian approach. International Journal of Innovation and sustainable development 8 (2), 167-189.

99. Ritthoff, M., Holger, R., Christa, L., 2002. Calculating MIPS: Resource productivity of products and services, Wuppertal Spezial, Wuppertal Institut für Klima, Umwelt und Energie, No. 27e, ISBN 3929944561, Retrieved on 28/3/2013, http://nbn-resolving.de/ urn:nbn:de:101:1-200910191108 http://hdl.handle.net/10419/59294.

100. Roca, L.C., Searcy, C., 2012. An analysis of indicators disclosed in corporate sustainability reports. Journal of Cleaner Production 20, 103-118.

101. Romli, A., Prickett, P., Setchi, R., Soe, S., 2014. Integrated eco-design decision-making for sustainable product development. International Journal of Production Research 53 (2), 549-571.

102. Rondinelli, D. and Berry, M., 2000. Environmental Citizenship in Multinational Corporations: Social Responsibility and Sustainable Development. European Management Journal 18 (1), 70-84.

103. Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Engineering 90, 1-10.

104. Saaty ,T.L., 2008. Decision making with Analytic Hierarchy Process. International Journal of Service Science 1 (1), 83-98.

105. Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill International, New York, NY, U.S.A.

106. Saaty, T.L., 1990. How to make a decision: The Analytic Hierarchy Process., European Journal of Operational Research 48 (1), 9-26.

107. Sadiq, R., Khan, F.I., Veitch, B., 2005. Evaluating offshore technologies for produced water management using *GreenPro-I*—a risk-based life cycle analysis for green and clean pro bcess selection and design. Computers and Chemical Engineering 29, 1023-1039.

108. Sakao, T., 2007. A QFD - centred design methodology for environmentally conscious product design. International Journal of Production Research 45 (18-19), 4143-4162.

109. Seghezzo, L., 2009. The five dimensions of sustainability, Environmental Politics 18 (4), 539-556.

110. Shalij, P.R., 2009. Design of ISO 9001:2000 based supply chain quality management system and its implementation studies in two typical Indian manufacturing companies. Thesis. Anna University Chennai.

111. Singh, R.K., Murthy, H.R., Gupta, S.K., Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. Ecological Indicators 15 (1), 281-299.

112. Sokolova, M.V., Fernandes-Caballero, A., 2009. Modeling and implementation of an agent-based environmental health impact decision support system. Expert Systems with Application 36 (2), 2603-2614.

113. Srivastava J., Connoly T, Beach L. R., 1995. Do Ranks Suffice? A Comparison of Alternative Weighting Approaches in Value Elicitation. Organizational Behavior and Human Decision Processes 63 (1), 112–116.

114. Starik, M., Kanashiro, P., 2013. Toward a Theory of Sustainability Management Uncovering and Integrating the Nearly Obvious. Organization and Environment 26 (1), 7-30.

115. Tahir,A.C., Darton,R.C., 2010. The process Analysis Method of selecting indicators to quantify the sustainability performance of a business operation. Journal of Cleaner Production 18, 1598-1607.

116. Tischner, U., Schmincke, E., Rubik, F., 2000. How to do Eco Design? – A guide for Environmentally and Economically Sound Design. Verlag form, Germany.

117. Triantaphyllou, E., Mann, S.H., 1995. Using the analytic hierarchy process for decision making in engineering applications: some challenges. International Journal of Industrial Applications 2 (10, 35-44.

118. Ugurlu, O., 2015. Application of Fuzzy Extended AHP methodology for selection of ideal ship for oceangoing watchkeeping officers. International Journal of Industrial Ergonomics, Retrieved on 18/2/2014, http://dx.doi.org/10.1016/j.ergon.2015.01.013.

119. Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J.W., Kara, S., Hermann, C., Dutlou, J.R., 2012. CIRP Annals-Manufacturing Technology 61, 681-702.

120. Veleva, V., Ellenbecker, M., 2001. Indicators of sustainable production: framework and methodology. Journal of Cleaner Production 9 (6), 519-549.

121. Vinodh, S., Rathod, G., 2010. Integration of ECQFD and LCA for sustainable product design. Journal of Cleaner Production 18 (80), 833–842.

122. Weaver, A., Pope, J., Morrison-S, A., Lochner, P., 2008. Contributing to sustainability as an environmental impact assessment practitioner. Impact Assessment and Project Appraisal 26 (2), 91-98.

123. Wei, G., Wang, J., Chen, J., 2013. Potential optimality and robust optimality multi attribute decision analysis with incomplete information: A comparative study. Decision support system 55, 679-684.

124. Wenzel H., Hauschild, M., Alting, L., 1997. Environmental Assessment of products, DTU, Denmark 1.

125. Yager, R.R., Gumrah, G., Reformat, M.Z., 2011. Using a web Personal Evaluation Tool - PET for lexicographic multi-criteria service selection. Knowledge-Based system 24, 929-942.

126. Yan, W., Chan, C-H., Chang, W., 2009. An investigation into sustainable product conceptualization using design knowledge hierarchy and Hopfield network. Computer and Industrial Engineering 56, 1617-1626.

127. Yan, P., Zhou, M.C., Sebastian, D., Caudill, R., 2002. Integrating Eco-Compass concept into integrated product and process development. International Journal of Environmentally Conscious Design and Manufacturing 10 (3), 6-16.

128. Yarwood, J. M., Eagan, P. D., 2009. Design for the Environment - Toolkit. Minnesota Office of Environmental Assistance. Minnesota. Retrieved on 16/4/2014, http://www.portaldeconhecimentos.org.br/index.php/por/content/view/full/11172.

129. Yoon, S.W., Velasquez, J.D., Patridge, B.K., Nof, S.Y., 2008. Transportation security decision support system for emergency response: A training prototype, Decision Support Systems 46 (1), 139-148.

130. Yuan, C., Zhai, Q., Dornfeld, D., 2012. A three dimensional system approach for environmentally sustainable manufacturing. CIRP Annals – Manufacturing Technology 61, 39-42.

131. Zhai, L.Y., Khoo, L.P., Zhong, Z.W., 2010. Towards a QFD-based expert system: extension to fuzzy QFD methodology using rough set theory. Expert System with Application 37, 8888-8896.

132. Zhang, Y., Wang, H., Zhang, C., 1999. Green QFD-II: a life cycle approach for environmentally conscious manufacturing by integrating LCA and LCC into QFD matrices. International Journal of Production Research 37, 1075-1091.

133. Zhou, C-C., Yin, G-F., Hu, X-B., 2009. Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach. Materials and Design 30, 1209-1215.

134. Ziout, A., Azab, A., Altarazi, S., ElMaraghy, W.H., 2013. Multi-criteria decision support for sustainability assessment of manufacturing system reuse. CIRP Journal of Manufacturing Science and Technology 6 (1), 59-69.