

MODELING AND ANALYSIS OF  
SUSTAINABLE PRODUCT DEVELOPMENT

by

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## **ABSTRACT**

### **MODELING AND ANALYSIS OF SUSTAINABLE PRODUCT DEVELOPMENT**

In this thesis, a methodological approach for sustainable product development is proposed. It consists of three fundamental phases which employ Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), Quality Function Deployment (QFD), and Data Envelopment Analysis (DEA). The life cycle analysis of the current system is the first phase. The processes which occur along the life cycle are separated, and their inputs and outputs are detected. These identified elements are analyzed with LCA from an environmental viewpoint, and with LCC emphasizing the economical issues. Customer requirements are identified, design alternatives are generated and compared with QFD in the second phase. From sustainability point of view, customer term is classified as external customer, internal customer, and society. Product design alternatives are then compared based on technical specifications and requirement satisfaction levels. In the last part of the methodology, DEA model based on critical criteria of sustainability is constructed. In accordance with this model taking into account inputs, desirable outputs, and undesirable outputs, each design alternative is evaluated and the most sustainable option is selected.

Based on the proposed approach, a case study is conducted for glass beverage containers. 24 design alternatives are constructed from the most crucial technical attributes based on the customer requirements. They are analyzed and assessed in accordance with the proposed methodology. As a result, four options are selected as more sustainable than the others. It is demonstrated that selection and evaluation of product design alternative can be performed in a systematic way. The integrated methodology provides a roadmap for modeling and analysis for sustainable product development to strengthen the competitive power of manufacturing companies.

## ÖZET

### SÜRDÜRÜLEBİLİR ÜRÜN GELİŞTİRMENİN ANALİZİ VE MODELLENMESİ

Bu çalışmada sürdürülebilir ürün gelişimine dair metodolojik bir yaklaşım sunulmuştur. Bu metodolojik yaklaşım üç temel aşamadan oluşmaktadır ve bu aşamalarda Yaşam Döngüsü Değerlendirmesi (YDD) ve Yaşam Döngüsü Maliyetlendirmesi (YDM), Kalite Fonksiyon Yayılımı (KFY) ve Veri Zarflama Analizi (VZA) araçları kullanılmıştır. Mevcut sistemin yaşam döngüsü analizi ilk aşamadır. Yaşam döngüsü boyunca oluşan süreçler birbirinden ayrılarak, girdi ve çıktılar saptanır. Sonrasında, belirlenen girdi ve çıktılar YDD ile çevresel bakış açısı ile analiz edilirken, YDM ile de ekonomik konular açıdan ele alınır. Metodolojinin ikinci aşamasında KFY ile müşteri istekleri belirlenir, ürün tasarım alternatifleri oluşturulur ve karşılaştırılır. Sürdürülebilirlik bakış açısıyla müşteri kavramı dış müşteri, iç müşteri ve toplum olarak sınıflandırılmıştır. Ürün tasarım alternatifleri, daha sonra teknik özelliklerine ve istekleri tatmin etme düzeylerine göre karşılaştırılmıştır. Metodolojinin son bölümünde ise sürdürülebilirlik açısından belirlenen önemli ölçütleri temel alan VZA modeli kurulmuştur. Girdiler, istenen çıktılar ve istenmeyen çıktılar ele alan bu modele göre her bir ürün tasarım alternatifi puanlandırılmış ve sonucunda en sürdürülebilir alternatif seçilmiştir.

Bu tezde öne sürülen yaklaşıma dayanarak, cam içecek şişelerinde örnek vaka çalışması yürütülmüştür. Müşteri ihtiyaçları yönünde en önemli teknik özellikler temel alınarak 24 tasarım alternatifi oluşturulmuştur. Bunlar sunulan metodolojiye göre analiz edilmiş ve değerlendirilmiştir, ve sonucunda dört tasarım seçeneği diğer alternatiflerden daha sürdürülebilir olarak belirlenmiştir. Böylece ürün tasarım seçimlerinin ve değerlendirmelerinin sistematik yollarla yapılabileceği kanıtlanmıştır. Bütünleştirilmiş metodoloji, üretim firmalarının rekabet gücünü güçlendirmek amacıyla sürdürülebilir ürün geliştirme için modelleme ve analiz yol haritası sağlamaktadır.

## TABLE OF CONTENTS

ACKNOWLEDGEMENTS . . . . .	iii
ABSTRACT . . . . .	iv
ÖZET . . . . .	v
LIST OF FIGURES . . . . .	ix
LIST OF TABLES . . . . .	xi
LIST OF SYMBOLS . . . . .	xiii
LIST OF ACCRONYMS /ABBREVIATIONS . . . . .	xv
1. INTRODUCTION . . . . .	1
1.1. Background . . . . .	1
1.2. Objectives . . . . .	2
1.3. Overview of the Tools and Techniques Employed. . . . .	3
1.4. Significance of the Study . . . . .	6
1.5. Organization of the Thesis . . . . .	7
2. SUSTAINABLE PRODUCT DESIGN AND DEVELOPMENT METHODOLOGIES 8	
2.1. Evolution of Sustainability Notion . . . . .	9
2.2. Sustainable Product Development . . . . .	11
2.3. Sustainable Product Design Methodologies . . . . .	15
2.3.1. Life Cycle Assessment . . . . .	15
2.3.2. Life Cycle Costing . . . . .	18
2.3.3. Traditional Quality Function Deployment . . . . .	20
2.4. Related Research Work. . . . .	23
3. PROPOSED METHODOLOGY . . . . .	26
3.1. Product Life Cycle Assessment . . . . .	27
3.2. Identification of Design Alternatives . . . . .	28
3.3. Optimal Design Selection. . . . .	35
3.3.1. The Basic Data Envelopment Analysis Model . . . . .	36
3.3.1.1. CCR Model... . . . .	38
3.3.1.2. BCC Model. . . . .	40
3.3.2. Environmental Data Envelopment Analysis. . . . .	41
3.3.2.1. Environmental Data Envelopment Analysis Approaches. . . . .	41

3.3.2.2. Environmental Data Envelopment Analysis Model. . . . .	43
4. THE CASE STUDY . . . . .	47
4.1. Life Cycle of Glass Containers . . . . .	47
4.1.1. Raw Materials . . . . .	47
4.1.2. Production . . . . .	48
4.1.3. Distribution . . . . .	49
4.1.4. Filling Operation and Usage . . . . .	49
4.1.5. End of Life. . . . .	51
4.1.5.1. Recycling . . . . .	52
4.1.5.2. Reuse . . . . .	53
4.1.5.3. Landfilling . . . . .	54
4.2. Life Cycle Inventory Assessment Application. . . . .	54
4.2.1. Raw Material Consumptions . . . . .	55
4.2.2. Emissions to Air . . . . .	56
4.2.3. Emitted Particulates . . . . .	57
4.3. Life Cycle Costing Application . . . . .	58
4.4. Quality Function Deployment Application . . . . .	60
4.4.1. Defining Customer . . . . .	61
4.4.2. Defining Customer Needs . . . . .	61
4.4.3. Defining Technical Attributes . . . . .	65
4.4.4. Constructing Relationship Matrix. . . . .	65
4.4.5. Correlation Matrix . . . . .	67
4.4.6. Comparison of Design Alternatives. . . . .	68
4.4.7. Scenario Analysis . . . . .	68
4.4.8. Comparison of Technical Attributes . . . . .	70
4.4.8.1. Raw Materials Index and Consumption Amounts . . . . .	70
4.4.8.2. Toxicity of Materials . . . . .	73
4.4.8.3. Color – Volume – Weight . . . . .	73
4.4.8.4. Height – Diameter – Thickness – Shape. . . . .	74
4.4.8.5. The Mass of Emissions and Other Pollutants . . . . .	75
4.4.8.6. Deposit System and Reverse Logistics . . . . .	77
4.4.8.7. Recyclability and Landfilling . . . . .	78
4.4.8.8. The Additional Attributes. . . . .	78

4.4.8.9. The Life Cycle Costs . . . . .	79
4.4.9. Comparison of Customer Satisfaction . . . . .	81
4.5. Environmental Data Envelopment Analysis . . . . .	84
5. CONCLUSIONS AND RECOMMENDATIONS . . . . .	88
5.1. Conclusions . . . . .	88
5.2. Contributions . . . . .	89
5.3. Suggestions for Further Research . . . . .	90
APPENDIX A: TECHNICAL SPECIFICATIONS OF SCENARIOS . . . . .	93
APPENDIX B: LIFE CYCLE POLLUTANT AMOUNTS OF SCENARIOS . . . . .	94
APPENDIX C: FLOW CHART OF THE SYSTEM . . . . .	103
REFERENCES . . . . .	104

## LIST OF FIGURES

Figure 1.1. Advantages of sustainable products . . . . .	2
Figure 1.2. Sustainability and employed tools . . . . .	5
Figure 2.1. Major milestones in the evolution of sustainability . . . . .	10
Figure 2.2. LCA framework . . . . .	16
Figure 2.3. Potential impact categories. . . . .	17
Figure 2.4. Systematic approach of QFD. . . . .	20
Figure 2.5. House of quality template . . . . .	22
Figure 3.1. Proposed methodology. . . . .	26
Figure 3.2. Product life cycle stages . . . . .	27
Figure 3.3. Customer requirements structure of enhanced QFD. . . . .	30
Figure 3.4. Environmental production system . . . . .	41
Figure 3.5. Productions sets of $P^w(x)$ and $P^s(x)$ . . . . .	45
Figure 4.1. Production process of glass . . . . .	48
Figure 4.2. End of life options for glass containers . . . . .	51
Figure 4.3. Roof part of HOQ . . . . .	67
Figure 4.4. Raw material and cullet usage amounts of scenarios . . . . .	72
Figure 4.5. Comparison of total emissions in scenarios. . . . .	75
Figure A.1. Container shape options . . . . .	93
Figure B.1. Comparison of manufacturing emissions in scenarios . . . . .	100
Figure B.2. Comparison of transportation emissions in scenarios . . . . .	100
Figure B.3. Comparison of usage emissions in scenarios . . . . .	101
Figure B.4. Comparison of recycling emissions in scenarios . . . . .	101
Figure B.5. Comparison of landfilling emissions in scenario . . . . .	102

Figure C.1. Flow chart of the system. . . . . 103

## LIST OF TABLES

Table 3.1. The external customer’s requirements. . . . .	31
Table 3.2. The internal customer’s requirements. . . . .	32
Table 3.3. The society’s requirements. . . . .	34
Table 3.4. CCR models. . . . .	39
Table 3.5. BCC models. . . . .	40
Table 3.6. Environmental data envelopment models . . . . .	46
Table 4.1. Recycling targets of glass in Turkey. . . . .	52
Table 4.2. Batch values for producing colorless/amber/green containers. . . . .	55
Table 4.3. Other resources for producing colorless/amber/green containers. . . . .	56
Table 4.4. Emissions of colorless containers. . . . .	57
Table 4.5. Emissions of amber containers. . . . .	57
Table 4.6. Emissions of green containers. . . . .	57
Table 4.7. Particulates through all life cycle. . . . .	58
Table 4.8. Cost data for one-way containers excluding end of life. . . . .	59
Table 4.9. Cost data for multi-way containers excluding end of life. . . . .	59
Table 4.10. Cost of end of life. . . . .	60
Table 4.11. Voice of customer. . . . .	64
Table 4.12. Relationship matrix. . . . .	66
Table 4.13. Compatibility matrix of various design elements. . . . .	68
Table 4.14. Scenarios - design alternatives. . . . .	69
Table 4.15. Raw material consumption amounts of scenarios. . . . .	72
Table 4.16. Unit glass container weights in scenarios. . . . .	74
Table 4.17. Total emission amounts of scenarios. . . . .	76

Table 4.18. Life cycle costs of scenarios. . . . .	80
Table 4.19. Customer satisfaction comparison matrix. . . . .	82
Table 4.20. Calculation of customer satisfaction from scenario – an example. . . . .	83
Table 4.21. Customer satisfaction comparison results. . . . .	84
Table 4.22. Correlations among model data. . . . .	85
Table 4.23. Results of environmental data envelopment model. . . . .	86
Table 4.24. Correlation between efficiency scores and model data. . . . .	87
Table A.1. Height – diameter – shape specifications of containers in scenarios. . . . .	93
Table B.1. Manufacturing emissions of scenarios. . . . .	94
Table B.2. Transportation emissions of scenarios. . . . .	95
Table B.3. Usage emissions of scenarios. . . . .	96
Table B.4. Recycling emissions of scenarios. . . . .	97
Table B.5. Landfilling emissions of scenarios. . . . .	98
Table B.6. Amount of other pollutants – bulk waste. . . . .	99

## LIST OF SYMBOLS

$a_n$	Absolute priority of nth technical requirement
$b_{lj}$	Amount of lth undesirable output for the jth DMU
$c_r$	Cost of life cycle stage r
$C$	Total life cycle cost
$CI_p$	Characterized effect value of environmental category p
$cw_m$	Importance rating of mth customer requirement
$E_j$	Efficiency score of DMU <sub>j</sub>
$EF_{pq}$	Characterization factor for intervention q within environmental category p
$Eff_p$	Effect factor “normal” for environmental category p
$j$	Index for DMUs
$i$	Index for inputs of DMUs
$k$	Index for desirable outputs of DMUs
$l$	Index for undesirable outputs of DMUs
$m$	Index for customer requirements
$n$	Index for technical attributes
$NI_p$	Normalized effect value of environmental category p
$p$	Index for environmental categories
$Q_q$	Amount of intervention q
$q$	Index for invention types
$R_+$	Positive real numbers
$R_{mn}$	The relationship between mth customer requirement and nth technical requirement
$r$	Index for life cycle stages
$TI$	Total impact of all environmental categories
$u_k$	Associated weight variable for the kth desirable output
$v_i$	Associated weight variable for the ith input
$w_p$	Weighting factor of environmental category p
$WI_p$	Weighted effect value of environmental category p
$x_{ij}$	Amount of ith input for the jth DMU

$y_{kj}$	Amount of kth desirable output for the jth DMU
$\theta_j$	Dual efficiency score of DMU <sub>j</sub>
$\lambda_j$	Dual weight variable of DMU <sub>j</sub>

## LIST OF ACCRONYMS /ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BCC	Banker, Charnes and Cooper
CCR	Charnes, Cooper and Rhodes
CH <sub>4</sub>	Methane
CO	Carbonmonoxide
CO <sub>2</sub>	Carbondioxide
CRS	Constant Returns to Scale
DEA	Data Envelopment Analysis
DfE	Design For Environment
DfX	Design For X
DMU	Decision Making Unit
DRS	Decreasing Returns to Scale
EPA	United States Environmental Protection Agency
EU	European Union
HOQ	House of Quality
IRS	Increasing Returns to Scale
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Inventory Assessment
LCC	Life Cycle Costing
NGO	Non-governmental Organizations
NO <sub>2</sub>	Nitrogendioxide
NMVOC	Non-methane Volatile Organic Compounds
OHSAS	Occupational Health and Safety Management System
PPS	Production Possibility Set
QFD	Quality Function Deployment
QFDE	Quality Function Deployment for Environment
SO <sub>2</sub>	Sulphurdioxide
TQM	Total Quality Management

TRI	Toxic Release Inventory
TRIZ	Theory of Inventive Problem Solving
UN	United Nations
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Voice of Customer
VOE	Voice of Engineering
VRS	Variable Returns to Scale
WCED	World Commission on Environment and Development

# 1. INTRODUCTION

## 1.1. Background

The competitiveness of a company is strictly influenced by the cost, the quality of the products and the capability of bringing products to the market in a timely manner. In this point of view, current practices of product development are predominantly based on traditional cost/profit models which aim to achieve high quality of a product with low cost and high profit. Apart from these factors, in recent years environmental concerns and sustainability are becoming other determinants in the area of product development, stimulating to change companies' product design procedures. Therefore, manufacturing of products which meet customer quality requirements, cost less, and possess sustainability features is now a crucial objective of any company competing globally.

In accordance with the definition of the World Commission on Environment and Development, "sustainable development" is the state of growth that meets the needs of the present circumstances without compromising the ability of future generations to meet their own needs (WCED, 1987). Moreover, "sustainability" refers to optimization of economic level of human activity within the supply limits of renewable resources and the accepted capacity of natural ecosystems. It is achieved with increased resource productivity and decreased material/energy load to the environment. In the case of product development, sustainable product is the one which satisfies the attributes mentioned in the sustainability definitions.

Sustainable products provide many advantages for companies, customers and society (Figure 1.1.). Environmental impacts are reduced or totally eliminated by less usage of energy and material, less wastes and emissions throughout the life cycle stages. In the social aspect, improved health and safety conditions of workers, end users, and inhabitants located in the vicinity of the company are obtained. Improved employee conditions in terms of equity, equality, and child labor are also desired.

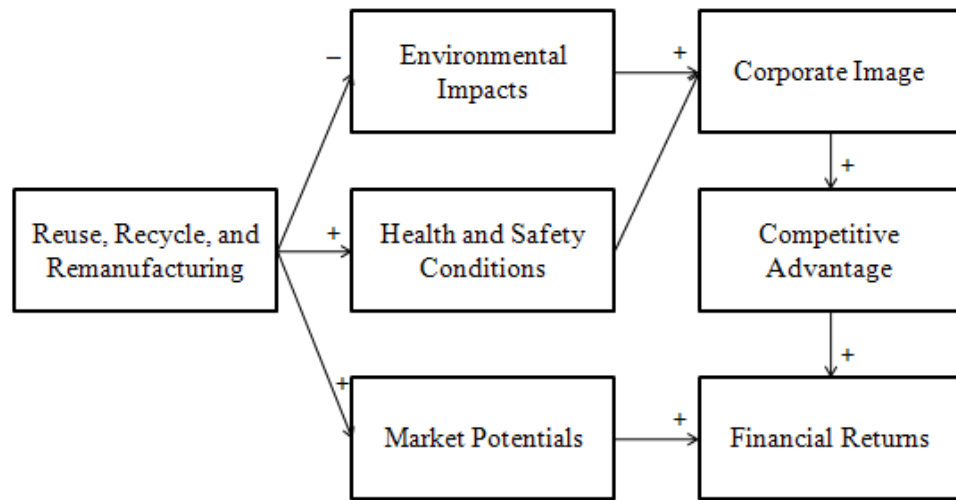


Figure 1.1. Advantages of sustainable products.

Promoted reuse, recycle, and remanufacturing options contribute to elimination of environmental impacts by less material usage; to social improvements by generating new work opportunities; to economy by making profits from used products, the reduction of manufacturing costs, the satisfaction of customer demands, and the lightening of regulatory burdens. Moreover, the need for sustainability triggers creativity and new markets formations. Additional market potentials and financial returns are the other gained advantages with improved economical conditions. As a consequence of all benefits, corporate image and reputation are improved, and competitive advantage is strengthened with sustainable products.

## 1.2. Objectives

The objective of this thesis is to establish a decision oriented life cycle system modeling approach that enables the integration of sustainability notion to product development process. The research problem mainly focuses on how to design and develop a product in a sustainable way for environment, society, and economy with consideration of product's all life cycle stages. Most of the current studies emphasizing "eco-design" and "design for environment" concepts focus on quality, cost, and environment separately. This study attempts to provide an integrated approach based on sustainability in a broader

perspective enhancing notion of customer and integrating different modeling and analysis tools.

In order to deal with the problem complexity, a life cycle approach is adopted that combines environmental, social, and economical factors at the early stage of the product design. The decision making problem is treated in a stepwise approach which consists of six stages listed as:

- Identifying the stakeholders and the customer segmentation of the product system under investigation,
- Analyzing the life cycle stages of the product by examining inputs and outputs of the processes,
- Collecting the environmental, quality, and cost requirements of customers,
- Developing potential design solutions as alternatives,
- Comparing the design alternatives in terms of raw material consumptions, emissions, and costs through life cycle stages and determining the satisfaction levels of the customer quality requirements,
- Selecting the most sustainable design alternative by combining environment, cost, and satisfaction levels in a decision making problem.

### **1.3. Overview of the Tools and Techniques Employed**

The proposed methodology assesses the sustainability of the product design alternatives in a multidimensional framework. It is an integrated methodology that incorporates four different tools and techniques. In the assessment of design alternatives Quality Function Deployment (QFD), Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) are utilized, and in the selection of the optimal design alternative Data Envelopment Analysis (DEA) is employed.

Quality function deployment (QFD) is a promising total quality management (TQM) methodology that translates needs and expectations of customer to technical specifications of product. The proposed QFD extends the traditional approach with detailed customer

segmentation and analysis of their categorized requirements according to life cycle stages. The crucial technical requirements are identified in QFD, and design alternatives are developed. The comparison for technical attributes of design alternatives is carried out, and the customer satisfaction levels from these design alternatives are evaluated in QFD.

Additionally, the environmental assessment of design alternatives is performed with life cycle assessment (LCA) methodology. This approach converts raw material consumptions and emission amounts of design alternatives to specified environmental impacts. In this thesis, LCA is only utilized for obtaining raw material consumptions and emission amounts, since these are correlated with environmental impacts.

Apart from the aforementioned approaches, cost analysis is executed with life cycle costing (LCC) methodology. In this part of the study, costs through all life cycle stages of design alternatives are listed, and total cost of the product is calculated.

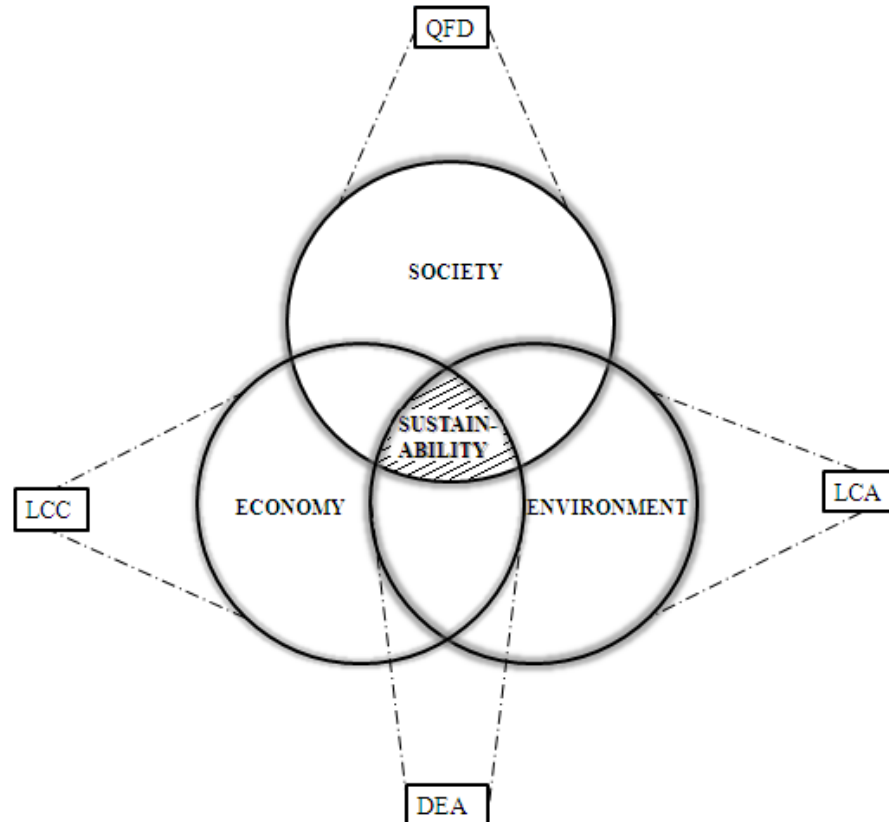


Figure 1.2. Sustainability and employed tools.

The proposed methodology is a combination of all these tools and techniques with some modifications in accordance with life cycle thinking as illustrated in Figure 1.2. Each tool which is summarized above symbolizes an element of sustainability as LCA stands for environmental aspect; LCC investigates economical aspect, and lastly QFD analyzes customer/society aspect. The approach integrating all of these elements and selecting the most sustainable design alternative is data envelopment analysis (DEA). DEA uses the cost data which is obtained from LCC, the data for raw material and emission amounts which are calculated in LCA and the customer satisfaction data assessed in QFD. By combining all inputs, DEA chooses the optimal design alternative which is the most sustainable design evaluation regarding with the aspects of customer, cost, and environment.

#### **1.4. Significance of the Study**

The systematic approach for the sustainable product development is an emerging field which attracts attention of numerous researchers as cited in Chapter 2. This thesis proposes a sustainable product development methodology and recommendations how to improve their products and processes by enhancing competitive power for manufacturing companies. Moreover, it is also intended to assist companies in addressing the issue of environmental protection, besides cost and customers' quality satisfaction levels.

The three core competitiveness factors quality, cost, and time effectiveness are elaborated together with sustainability. In the process of sustainability adaptation, many companies fail to implement the related critical success factors. However, in this process the most crucial challenge that companies face with is their view of underestimating sustainability notion considered with other competitive criteria. Since environmental adaptation causes costs and decreases profits at the beginning of the projects, some companies cannot cope with tradeoffs among competitiveness criteria. In this thesis, it is aimed to optimize all sustainability elements and to propose a methodology to ensuring competitiveness.

Methodological approaches in the early design phase and appropriate product development tools are required for a successful sustainability application. In this thesis, the

companies are introduced with life cycle thinking as the integrated methodology which also provokes them to analyze the product as a system that includes life cycle stages and different stakeholders. Another success factor is obtaining multidimensional perspective of sustainability. The proposed methodology of the thesis enables it by combining economical, environmental and quality analysis together. Moreover, the awareness and commitment of management are critical for sustainability motivation. It is important to consider all stakeholders of the system for total sustainability. In this study, it is obtained by segmentation of customer term as external customer, internal customer and society.

### **1.5. Organization of the Thesis**

The thesis is composed of five chapters. Chapter 1 presents an overview of the study. Chapter 2 covers the literature review and the necessary theoretical background to assist reader in understanding the methodologies. Additionally, crucial notions of sustainability, sustainable product development and the mostly utilized tools namely, quality function deployment, life cycle assessment, life cycle costing, data envelopment analysis are discussed more extensively. Chapter 3 defines proposed methodology which describes modifications in the employed tools and the integration points of tools. Methodology consisting of three phases covers all the sustainability elements and brings a systematic modeling approach to sustainable product development area. Chapter 4 applies the proposed methodology in the case of glass beverage container design and development. In accordance with proposed methodology, glass beverage container design alternatives are generated and the most sustainable option is selected. Chapter 5 concludes the study, by giving the implications and research contributions, and the recommendations on some future possible extensions of this work.

## **2. SUSTAINABLE PRODUCT DESIGN AND DEVELOPMENT METHODOLOGIES**

The studies on sustainable products can be traced back to the notion of “design for environment” and evolved in parallel with the customer needs and expectations. In order to present the state of the art for sustainable product development, this chapter is devoted to a literature survey focusing on related process models and design methodologies. The scope covers the theoretical developments in this area as well as the industrial applications reflecting the best practices. In this way, it is intended to identify the potential improvement areas and propose recommendations for further progress.

The application tools of environmental and sustainable product design can be classified into product development tools, decision making tools, and benchmarking tools. By considering the analysis of each one, product development methodologies such as quality function deployment (QFD), life cycle assessment (LCA) and life cycle costing (LCC) are mostly utilized tools. There are additional decision making tools employing checklists and matrices. Moreover, benchmarking is another evaluation tool considering physical quantities or environmental factors. Lastly, other perspectives taking into account hazard and risk assessment, stakeholder benefits, and feasibility studies are also applicable.

In this thesis, QFD is chosen as a design tool and extended with a life cycle view. LCA and LCC are supplementary assessment tools of design alternatives. Apart from the literature, the selection of the most sustainable option is obtained with a linear mathematical model which is based on data envelopment analysis. Following sections present features and characteristics of sustainable products, related tools, and works in this area.

### **2.1. Evolution of Sustainability Notion**

Figure 2.1 presents the evolution of sustainable products through the years. It dates back to environmentally conscious design which addresses parameters to plans, programs,

policies, buildings, or products. One of the most significant initiatives on sustainability dates back to 1968 when “Club of Rome” is founded. It is a global think tank which deals with the considerations for the future of humanity. It is composed of current and former Heads of State, United Nations bureaucrats, high level politicians and government officials, diplomats, scientists, economists, and business leaders from around the globe. Club of Rome raises considerable public attention with “The Limits to Growth” which models the consequences of a rapidly growing world population and finite resource supplies (Meadows et al., 1972). At the same year, “Stockholm Declaration”, is adopted by the United Nations at the 21st plenary meeting as the first document in international environmental law to recognize the right to a healthy environment (UNEP, 1972).

The concept of “Cradle to Cradle” is first coined for expressing the economy in loops and its impact on job creation, economic competitiveness, resource savings and waste prevention by W.R. Stahel (1976) who is the founder of The Product Life Institute. Later, “Triple Bottom Line” notion is defined by Freer Spreckley (1981) for taking into account ecology, society and economy. Afterwards, “Sustainable Development” is defined by Brundtland Commission, which is formally World Commission for Environment and Development, and sustainability started to be on the agenda of many people (WCED, 1987).

Another milestone of sustainability is “Hannover Principles” which is a set of statements about designing buildings and objects with forethoughts about their environmental impact, their effect on the sustainability of growth, and their overall impact on society (McDonough and Braungart, 1992). The United Nations’ studies on sustainability continue with “The Rio Declaration on Environment and Development” which is stated at United Nations Conference on Environment and Development, informally known as the “Earth Summit”. It is consisted of twenty seven principles intended to guide future sustainable development around the world (UNEP, 1992).

The sustainability for products is defined as Sustainable Product Design notion, which is emerged at an International Symposium on Sustainable Consumption in Oslo, Norway in 1994. It is expressed for the use of goods and services that respond to basic

needs and bring a better quality of life, while minimizing the use of natural resources, toxic materials and emissions of waste and pollutants over the life cycle, so as not to jeopardize the needs of future generations.

The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change, aimed at fighting global warming. It is initially adopted on 1997, and entered into force on 2005. Under this protocol, thirty seven countries commit themselves to a reduction of four greenhouse gases which are carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, and two groups of gases including hydrofluorocarbons and perfluorocarbons produced by them, and all member countries give general commitments. Moreover, United Nations encourage businesses worldwide to adopt sustainable and socially responsible policies, and to report on their implementation. The “Global Compact” is a United Nations initiative which is a principle-based framework for businesses, stating ten principles in the areas of human rights, labor, the environment and anti-corruption (UN, 1999). Another milestone launched in 1999 is the “Dow Jones Sustainability Index”. It measures companies’ sustainability initiatives by assessing their long term economic, social and environmental asset management plans.

Ten years after the first Earth Summit, the second one takes place in Johannesburg, South Africa (UNEP, 2002). It is also called as “The World Summit on Sustainable Development”. Most recently, the transformation of ecologically intelligent design is emphasized in the book entitled “Cradle to Cradle: Remaking The Way We Make Things” (McDonough and Braungart, 2002) and Limits to Growth is published again with modifications (Meadows et al., 2004). Additionally, in 2006, “An Inconvenient Truth” is released which is a documentary film formed by United States Vice President Al Gore's campaign to educate citizens about global warming. Finally, it can be concluded that over the years many positive events occurred in development of sustainability area and we can surely expect more in the future.

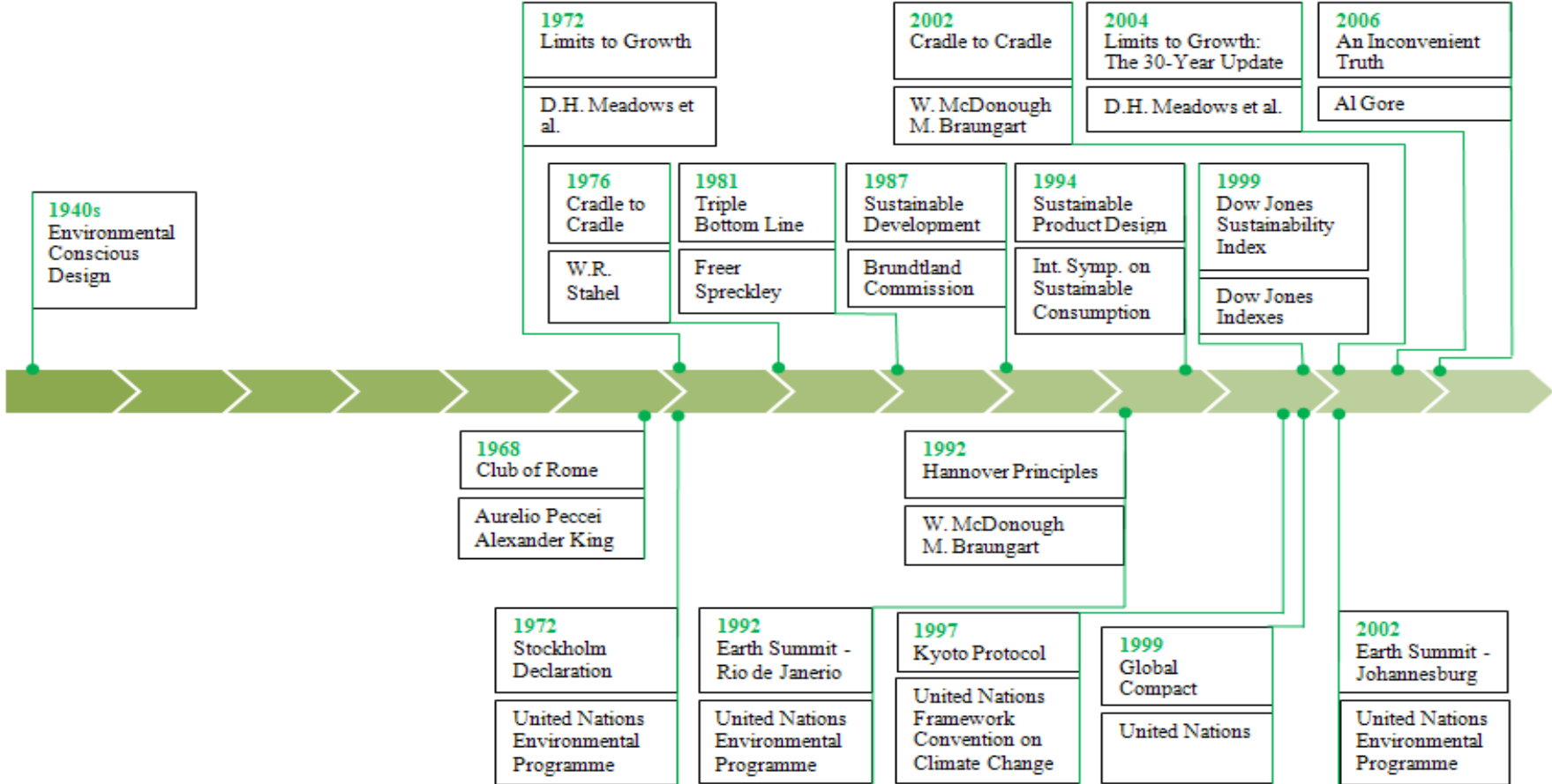


Figure 2.1. Major milestones in the evolution of sustainability.

## 2.2. Sustainable Product Development

Product development process covers the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery. Ertas and Jones (1996) define it as a process which starts with an identified need and concludes with satisfactory qualification and acceptance testing of the prototype. This restricted process scope emphasizes design phase up to full production and market launch. Our perspective in this thesis will be broader and in agreement with the definition stated by Ulrich and Eppinger (2000) including the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product.

The increasing importance of environment in recent years triggers the notion of “Design for the Environment (DfE)”. In this scope, environmental considerations are integrated into the design of a product, process, and/or technology (Allenby, 1993). Environmentally conscious design methodologies are acknowledged to be equivalent to “Design for Environment”, “Life Cycle Design”, “Green Design”, and “Eco-design”. The objective of these methodologies is identified as eliminating the negative effects of a product on the environment through all life cycle stages, especially at use and end of life stages. General approach is to use renewable and recyclable resources as much as possible with promoting “Design for X (DfX)” concept in which X may stand for environment, remanufacturing, and disassembling.

In the literature, there is a growing number of studies focusing on the integration of environmental aspects into product development. These efforts can be classified into three groups which are design methodologies, tools, and case studies. One of the pioneering works of environmental design is conducted by Lenox and Ehrenfeld (1997). Simon et al. (2000) emphasize the design for environmental decision support project which develops appropriate tools and methods for eco-design as well as finding the integration ways to the product development process. Santos-Reyes and Lawlor-Wright (2001) study ISO 14001 which is an environmental management system for design process. Handfield et al. (2001) investigate the reasons of the gap between theory and practice in environmentally designed products. Johansson (2002) and Pujari et al. (2003) deal with the underlying dimensions of

environmental new product development and influential factors of success and performance. Berchicci and Bodewes (2005) illustrate the growing importance of environmental issues on the new product development process.

Apart from these environmental considerations, sustainable product design is a broader concept which captures social, environmental, and economical aspects. The dimensions of sustainability are also referred as “triple bottom line”. It is also known as “the three pillars” which stands for planet, profit and people. In this viewpoint, environmental products have fewer attributes than sustainable ones, since they do not contain aspects of society and economy. The objective of sustainability is to achieve product designs which eliminate/reduce environmental and negative social impacts, and increase economical benefits of products from conception phase to end of life phase. Moreover, the society dimension of sustainability includes not only the current society but also future generations. Many DfE tools are only concentrated on minimizing the negative environmental impacts of products. On the other hand, sustainability calls for a radical change which is a switch from a “cradle to grave” pattern to “cradle to cradle” pattern. Cradle to cradle design enables the creation of wholly beneficial industrial system driven by the synergistic pursuit of positive economic, environmental and social goals. Extended concept namely sustainable design becomes the new trend in competitive world, and this fact shifts the paradigm of environmental design process (McDonough and Braungart, 2002).

The sustainable product notion is customer centric incorporating all the stakeholders influenced by the product. The major actors are external customers and internal customers including employees who are responsible for production, remanufacturing, disassembling, recycling, and waste disposing, and also suppliers. Government, non-governmental organizations (NGOs) and other relevant actors in the society are also taken into account in accordance with a system view for this interrelated complex process. The needs and expectations of these stakeholders dynamically evolve and a pivotal role in the competitive power of the companies. Some of the most notable motivating factors of sustainable products are listed as in the following:

- **Customer Demand:** Increase in the concerns on environmental issues among customers provides social pressure for sustainable development. By this awareness, green products are preferred more than others even if they are more expensive. Additionally, suppliers are the main indicator of quality and sustainability of the product, and industrial customers such as original equipment manufacturers do not want environmental liability for a supplier's product.

- **Legislations and Regulatory Mandates:** Government attends to promote sustainability with its regulations and legislations. There are specifications on emissions standards for air, water, and solid wastes. For instance, Ministry of Environment and Forestry releases regulation for the control of the packaging waste. Not only do some countries such as Japan and European Union (EU) have set product take-back programs, but also Environmental Protection Agency (EPA) emphasizes the severity by publishing the Toxic Release Inventory (TRI) which includes banned materials and reports requirements. Furthermore, in social area occupational safety and health standards play a crucial role. Economic incentives also exist for the activities of companies in environmental protection area. Recycling infrastructure is supported by regional municipalities. These restrictions force the industry to reduce their environmental impacts and encourage the municipalities to recycle at a specific percentage.

- **Standards and Certificates:** There are three major certificates that promote sustainability. The first one is ISO 9001 which is the most commonly used international standard that provides a framework for Quality Management Systems. It aims better quality, higher productivity, greater customer satisfaction, and greater profit. The second one is ISO 14001 which is the environmental management standards, has become a crucial element in business like quality management standards. It intends to obtain better environmental performance, greater eco-efficiency, greener products, and more transparency for and acceptance by external environmentally concerned stakeholders. Lastly, OHSAS 18001 concerns about employees and can be thought as the part of sustainability's social side. This certificate ensures safer and healthier workplaces, more efficient work processes, improved employee perceptions of the working environment, and greater recruitment attractiveness.

- **Eco-Labeling Programs:** Eco-label identifies a product that meets environmental performance criteria or standards in Europe which points the greenness of the product and brings a competitive advantage to the company. Eco-labels vary with respect to application areas. For instance, some labels quantify pollution or energy consumption by way of index scores or units of measurement, and others simply assert compliance with a set of practices or minimum requirements for sustainability or reduction of harm to the environment. Products which are awarded with flower logo allows to consumers to identify them easily. Eco-label certifies that the specified product is the most environmentally-friendly in its class and enables high level of transparency, reliability and scientific credibility. It is designed to promote products which have a reduced environmental impact compared with other products in the same product group and provide consumers with accurate and scientifically based information and guidance on products (European Parliament and the Council, 2000).

The sustainability notion and sustainable product development are studied more recently. Maxwell and Vorst (2003) provide guidance for developing sustainable products and services for industry and business. Their methodology is based on analyzing the products and services with a checklist consisting of functionality, life cycle stages, supply chain dynamics and sustainability impact factors. Kaebernick et al. (2003) modify traditional product development process with environmental requirements for obtaining sustainable development. The metrics of assessing the general sustainability index of a company are discussed by Labuschagne et al. (2005). Maxwell et al. (2006) add a functional and system approach to sustainable product and service development literature. Howarth and Hadfield (2006) argue the benefits and risks for sustainable product design. Waage (2007) suggests a road map for integrating sustainability to product development process. Ny et al. (2008) assess the sustainability of a product in the concept of sustainability by an expert guided template. Since all of these studies are qualitative, the need of a quantitative study is apparent and this thesis is an effort to serve that need.

### **2.3. Sustainable Product Design Methodologies**

In this study, quality function deployment, life cycle assessment, and life cycle costing methodologies are introduced as sustainable design tools. The review covering these topics is presented in the following sections. Based on this introduction and literature review, an integrated structure is created for proposed methodology in Chapter 3.

#### **2.3.1. Life Cycle Assessment**

Life cycle assessment is the methodology of quantifying the consumption of resources and assessing the environmental impacts of products or processes. The method evaluates the entire life cycle of the product, processes encompassing extracting and processing material, manufacturing, distribution, use, reuse and maintenance, recycling, and disposal.

LCA is mostly presented as the tool of environmental product management (Krozer and Vis, 1998). By evaluating the entire life cycle and the associated environmental affects, LCA identifies opportunities to improve environmental performance (ISO, 1997). There are different LCA usage areas in product planning and development to identify significant environmental aspects and to quantify environmental impacts. At the product level, it is utilized for determining environmental improvement opportunities such as recyclability, whereas at the component level, it is applied for material selection and reduction. Moreover, it is also a benchmarking tool for environmental products.

As previously mentioned, LCA is the technique to assess the potential environmental impacts of sustainability associated with a product throughout its life cycle. This analysis is composed of four steps which are depicted on Figure 2.2 (ISO 14040).

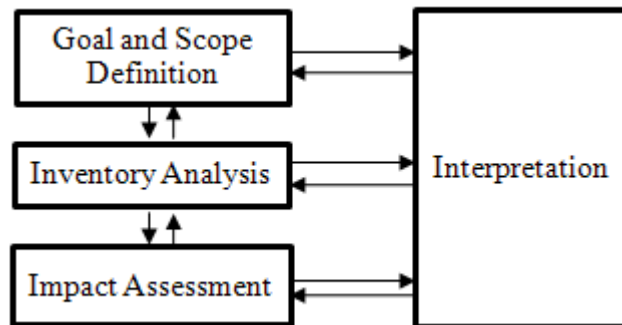


Figure 2.2. LCA framework.

- **Goal and Scope Definition:** At the beginning of the analysis, the aim and scope of the project are specified. Afterwards, assumptions, functional unit, and system boundaries are determined. Definition of scope includes identification of the production system and limits. Functional unit is the amount of products that is going to be assessed, and which also establishes the dimensions of the study. By these definitions, not only is product described in terms of assumptions, functional unit, and system boundaries; but working plan of LCA study is also determined.
- **Inventory Analysis:** Inputs and outputs of the product throughout its life cycle stages are listed and analyzed for each unit process within the system boundary in inventory analysis stage. Process inputs are raw materials and intermediate products; and outputs are emissions and wastes. These components are identified for each life cycle stage and reciprocal affects are measured by giving qualified metrics.
- **Impact Assessment:** Impact assessment includes steps which are section of impact categories and indicators, classification of inventory data into impact categories, characterization of inventory data within each category, normalization, weighting the characterized results.

There are various environmental impact categories which are confirmed by the LCA methodology (Figure 2.3). According to the potential impacts, there are three main categories which include resource depletion, human health impacts, and ecological impacts. In impact assessment, analyst selects the categories that are going to be assessed, and classifies inventory data in accordance with them.

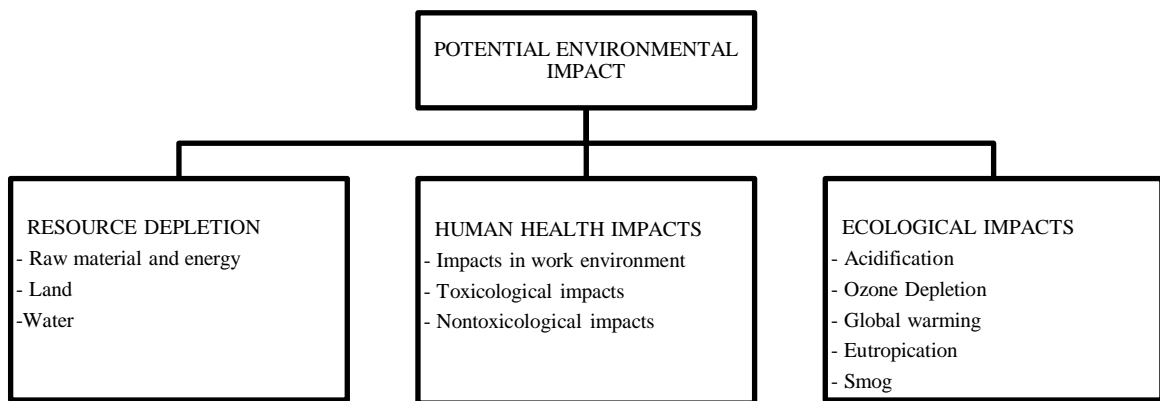


Figure 2.3. Potential impact categories.

The characterization is necessitated to equalize each inventory in the same environmental impact class. Summation of all units of measurement is not a reasonable calculation for LCA, since some inputs and outputs make more contribution to environmental impact than others. Therefore, characterization is performed by multiplying each input and output with an equivalence factor before getting an overall sum.

$$CI_p = \sum_q EF_{pq} * Q_q \quad p = 1,2, \dots n \quad (2.1)$$

$CI_p$  = Characterized effect value of environmental category p

$Q_q$  = Amount of intervention (emission, resource extractions or land use) q

$EF_{pq}$  = Characterization factor for intervention j within environmental category p

Afterwards in the normalization step, all characterized environmental effect values are adjusted on a determined normal scale.

$$NI_p = \frac{CI_p}{Eff_p} \quad p = 1, 2, \dots, n \quad (2.2)$$

$NI_p$  = Normalized effect value of environmental category p

$Eff_p$  = Effect factor “normal” (space, time, environmental category p)

In completion of impact assessment, different contributions towards effect are calculated in order to obtain weighted sum of their total amounts:

$$WI_p = w_p * NI_p \quad (2.3)$$

$$TI = \sum_p WI_p \quad (2.4)$$

$WI_p$  = Weighted effect value of environmental category p

$w_p$  = Weighting factor of environmental category p

$NI_p$  = Normalized effect value of environmental category p

$TI$  = Total impact of all environmental categories.

- Interpretation: The last step of LCA covers drawing conclusions from the results. Significant aspects and areas of environmental improvement are identified. Conclusions and recommendations are presented. Additionally, alternative processes are compared as a part of interpretation (Seppala, 2003).

### 2.3.2. Life Cycle Costing

Life cycle costing is the methodology of economical assessment of the product design decisions. The life cycle costing process includes identification of items to be monitored, specification of the cost structure, definition of links to estimate costs, and establishment of a method for formulating life cycle costs (Woodward, 1997).

The cost of product is perceived as the production cost by manufacturers, and the purchase price by the consumers. However, in accordance with life cycle thinking and system view there exist many other intangible costs which are associated with the product. Thus, the objective of LCC is to calculate the total cost of the product in its entire life cycle. By considering the total cost, it consists of cost components related to material acquisition, production, distribution, usage, recycling, and landfilling belonging to different stakeholders of the system. Therefore, LCC examines all cost elements occur in the life cycle of a product, and establishes the most appropriate methodology to sum up these costs and find the real cost of the product to the society.

An example of basic life cycle cost calculation is formulated as:

$$C = \sum_{i=1}^5 c_r \quad (2.5)$$

where  $c_r$  stands for life cycle stage cost,  $r$  representing the life cycle stages namely, raw materials, production, usage, distribution, and end of life. In accordance with life cycle stages, cost of acquisition includes direct purchase cost of raw materials, their handling and transportation costs. There exist costs in the production which are correlated with manufacturing cost, labor and other material costs, training and management costs, occupational liabilities, costs of waste minimization efforts. Additionally, cost of use means the direct costs occur in the usage of the product as well. The cost of end of life includes the costs such as landfilling cost and recycling costs, and the costs of other related activities such as cost to society which is the long term costs that affect the society (Fiksel, 1996).

Basic calculation may be simple, but the full methodology usually has some cost models and complex steps to implement (Fabrycky et al., 1991). LCC is a systematic and analytical process for evaluating various designs. Although it can be performed on its own, it is usually applied in parallel of LCA study and performed for the same product, functional unit, and system boundaries.

### 2.3.3. Traditional Quality Function Deployment

Quality function deployment (QFD) is a method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process (Akao, 1990). In this viewpoint, QFD is composed of four main phases: product planning, part deployment, process planning, and production planning (Hauser and Clausing, 1998). Each phase uses the specified elements of previous phase. All of these phases systematically form the requirements of the whole system levels that are included in the product planning and development. Firstly, product planning is the initial phase in which customer requirements are turned into technical requirements. Second phase is called as part deployment forming part characteristics of product based on the technical requirements obtained at first phase. Part characteristics from the second phase are considered in determination of key process operations in third phase, process planning. Finally in order to establish the production requirements, key process operations are specified in the fourth phase called production planning. Figure 2.4 displays this systematic framework (Hauser and Clausing, 1998).

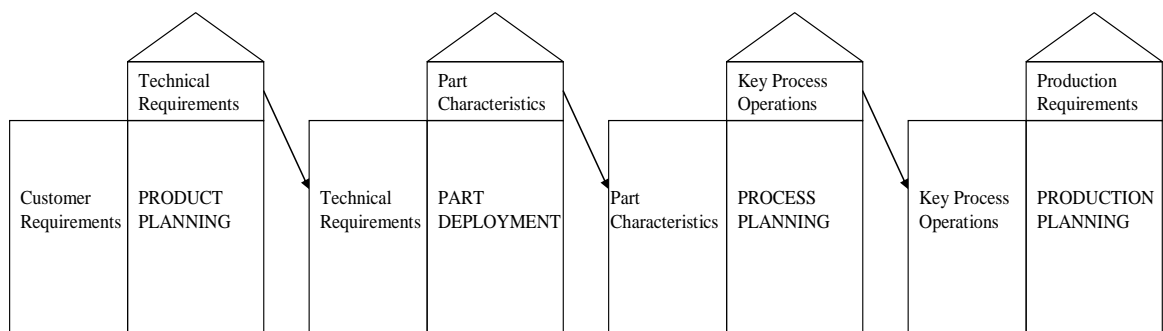


Figure 2.4. Systematic approach of QFD.

The most vital tool of QFD is known as the house of quality (HOQ). This is visual instrument structured as matrices storing information in a systematic way. The first HOQ is used for identifying customer requirements, establishing priorities of design requirements to satisfy the customer requirements, determining the relationship between customer requirements and technical specifications, and correlations between technical

specifications. In addition to identifying characteristics which are critical for satisfying customers, it also provides targets for these characteristics based on competitive benchmarking. Higher customer satisfaction is guaranteed with established true needs of customers via minimization of conflicting requirements and via importance rating. Moreover, it ensures the conformance of all product characteristics with customer requirements via systematic correlation and traceability. The six parts forming a HOQ are illustrated as a template in Figure 2.5.

- Customer Requirements - An effective design begins with identification of customer requirement which are depicted under the question form of ‘what are the customer requirements?’. The response is corresponded customers’ desires and expectations, and often called as ‘Voice of Customer (VOC)’.

- Planning Matrix - Planning matrix includes numerical evaluations of survey researches. Customers’ perceptions of the relative importance of the expressed needs are expressed as ‘Importance Ratings’. It quantifies priorities of requirements, and if it is the case of existing product it includes customer satisfaction ratings as a result of benchmarking study, sales point, and improvement factor.

- Technical Requirements - Satisfying customer requirements at the maximum level relies on design objective. The key method so as to attain the customer satisfaction is to ask ‘how can the customer requirements be satisfied?’. Therefore, the needed technical specifications of the product can be specified ‘Voice of Engineering (VOE)’ which is listed in this section.

- Interrelationship Matrix - The main part of the HOQ is interrelationship matrix, which is the part of defining the associations of technical requirements and the customer requirements. For each cell in this section, the designer assigns a symbol reflecting the extent of relationship between the technical requirement in the column and the customer requirement in the row.

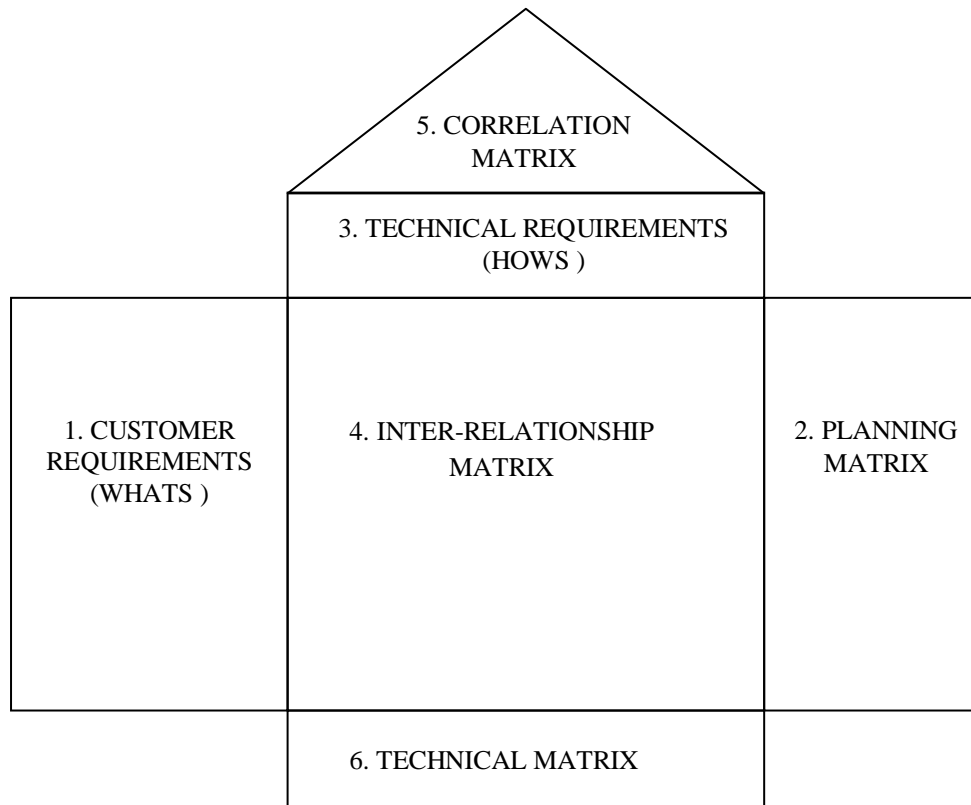


Figure 2.5. House of quality template.

- **Correlation Matrix** - The correlations among technical requirements are considered in the correlation matrix. These correlations also comprise the trade-offs among the various technical specifications.

- **Technical Matrix** - The summary of the QFD application results are calculated and listed in the technical matrix. The first section is the technical priority in which the importance level of a technical requirement in satisfying customer requirements is calculated in accordance with interrelationship matrix and planning matrix. The absolute priority of technical requirement  $n$  is formulated as:

$$a_n = \sum_m cw_m .R_{mn} \quad n = 1,2,\dots,s \quad (2.6)$$

where customer requirements are denoted by  $m=1,2,\dots,p$  and technical requirements are denoted by  $n=1,2,\dots,s$ .

$a_n$  = The absolute priority of  $n$ th technical requirement.

$R_{mn}$  =The relationship between  $m$ th customer requirement and  $n$ th technical requirement presented in the interrelationship matrix.

$cw_m$  = Importance rating of  $m$ th customer requirement.

The targets and benchmarking of company's product against to competitor's product are analyzed in the other two sections of the technical matrix. These sections provide data to management so as to elicit decisions in allocating resources about the design. Furthermore, they enable to evaluate the existing product against competitors using technical measures.

#### **2.4. Related Research Work**

The structure of QFD is always being developed in accordance with the new trends in product design area. One of the pioneering studies of the integrated environmental considerations in QFD is carried out by Zhang and Wang (1999). Their modified QFD expresses environmentally consciousness in QFD with life cycle analysis (LCA) and life cycle costing (LCC). In their viewpoint, the three dimensions of sustainability are analyzed separately. Quality house, green house, and cost house are developed with regarding to VOC, LCA, and LCC respectively for identifying technical requirements. Afterwards, they combine these houses in a concept comparison matrix for concept generation and process/product development phases.

In another study related with this area, Rahimi and Weidner (2002) present design for environment methodology at the quality function deployment template by adding an "Environmentally Responsible Product Assessment Matrix" to the house of quality (HOQ). As a result of this addition, all requirements of quality, environment, and cost are explicitly defined in one house of quality template for product base and component base study.

Kaebernick et al. (2003) modify QFD in a three dimensional way for sustainable product development with considering environmental requirements. These three dimensions consist of customer requirements, technical attributes and environmental metrics. Likewise, economical analysis is performed apart from the QFD for only end of life options.

From the studies on design for environment, analyzing separately quality, cost and environment as in Zhang and Wang (1999) or in a combined way as in Rahimi and Weidner (2002) differ from our study in the view of customer. They examine requirements of customer in the quality aspect whereas we propose it in the sustainability aspect. In the sustainability aspect, customer is not only the end user demanding quality requirements. Customer is defined as a group consists of end user, employees, and society expressing their requirements from a product.

Masui et al. (2003) identify environmental voice of customer and environmental voice of engineering in applying DfE to QFD, and call this argument as quality function deployment for environment (QFDE). It is also reasonable to take into account VOC and VOE from an environmental viewpoint, however it is not sufficient for sustainability. This constructed QFDE only considers environmental requirements. Study is constrained with QFD, so that design alternatives are not generated and assessed. Later, Sakao (2007) continues the study of QFDE and combines LCA and TRIZ methodologies with this QFDE template. In this study, product concepts are also generated with TRIZ, since TRIZ is an effective tool of finding solutions to conflicting design parameters, and evaluated with LCA for environmental analysis. In QFD studies which are covered in this section, life cycle stages are not integrated into customer requirements. Only in the study of Kobayashi (2006), life cycle phases are focused on for identifying inventory loads and their environmental needs in eco-specification matrix.

In accordance with the design problems, QFD methodology is also enhanced by quantitative methods such as operations research and management science applications, marketing research techniques, and fuzzy logic integration. For instance, Halog (2004) employs fuzzy linguistic decision support system in the selection of sustainable product improvement alternatives with data uncertainty. After combination of LCA, QFD, and

LCC, fuzziness is added to the study due to the data uncertainty. On the other hand, in order to define a life cycle planning methodology, integrated TRIZ method and QFD for early design, and LCA for evaluations after design are proposed by Kobayashi (2006). In this study, uncertainties in the design phase are also considered with Monte Carlo simulation.

Kahraman et al. (2006) incorporate the fuzzy analytic network process (Fuzzy-ANP), fuzzy analytic hierarchy process (Fuzzy-AHP), and fuzzy-QFD in the product design study. A mixed integer programming model is also constructed in the proposed framework. Choi et al. (2008) propose a methodology that determines the best DfE strategy based on the results of the product's environmental performance which is captured from the life cycle assessment (LCA). Afterwards, a multi-criteria decision making process is suggested to integrate the business aspects of product design. The final optimized decision is selected that is based on the rating score from the analytic hierarchy process (AHP).

By considering the results of literature survey, product design and development are not reasonably simple in practice. Although large numbers of individual design methods and tools have been generated due to shortcomings of developed design guidelines, most of them have limited aspects and are not capable of solving the problem completely. Thus, new sustainable framework model is generated which will be discussed in the next chapter.

### 3. PROPOSED METHODOLOGY

The proposed methodology is an integrated framework which includes three phases adopting life cycle view in all steps: Product Life Cycle Assessment, Identification of Design Alternatives, and Optimal Design Selection. It is displayed in Figure 3.1 and summarized in Sections 3.1, 3.2, and 3.3. The first phase which is called product life cycle assessment provides general information about the product system by the examination and analysis of the life cycle stages. In the second phase, design alternatives are identified and assessed. Identification of design alternatives enables to generate design options and to benchmark them. The most crucial part is the third phase where optimal design is selected. Optimal design selection contains a mathematical programming model which determines the most sustainable design.

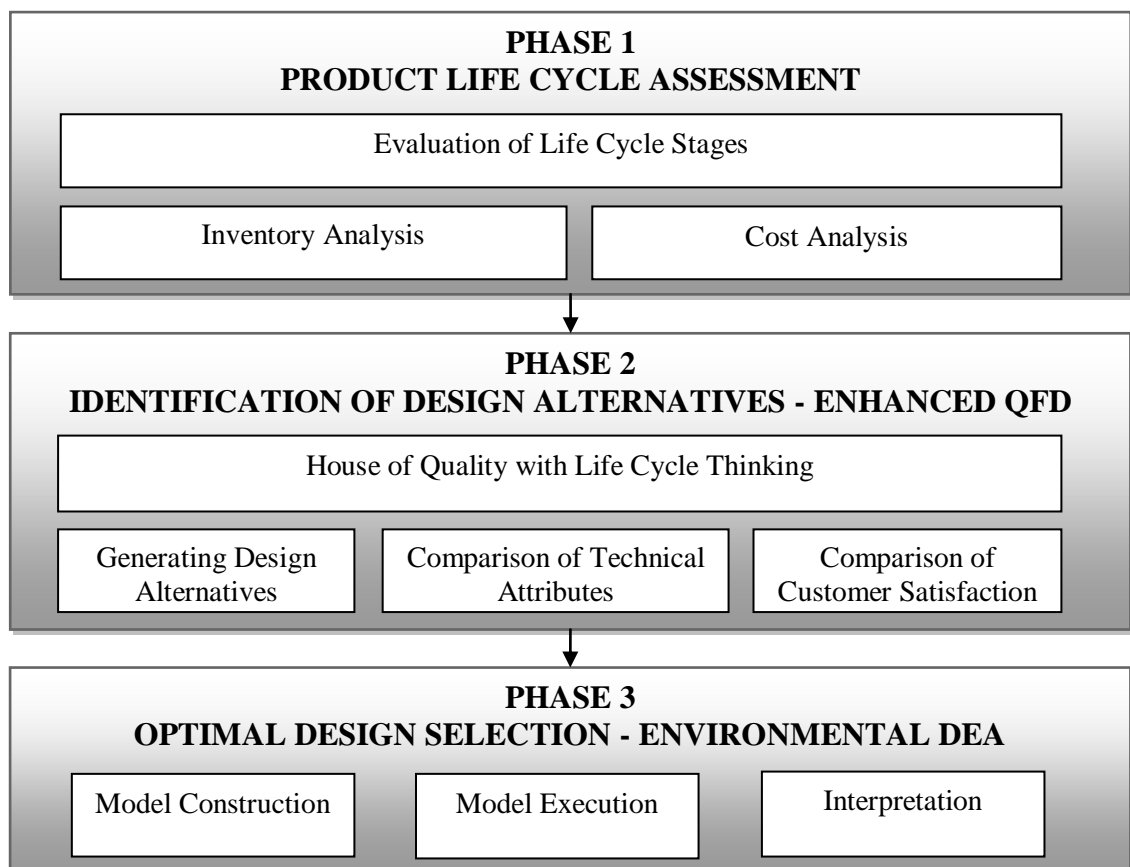


Figure 3.1. Proposed methodology.

### 3.1. Product Life Cycle Assessment

The first phase of the proposed methodology is the product life cycle assessment which investigates the current situation. Therefore, it is also referred “as-is product analysis”. It is performed in three main steps:

- Evaluation of life cycle stages,
- Inventory analysis,
- Cost analysis.

Life cycle stages are identified for a selected product. The entire life cycle of the product consists of a set of activities and processes where each one of them consumes a certain amount of resources and energy, goes through a series of transformations and triggers various emissions. The concept of life cycle adapts a system vision over the product’s input–output processes during all phases, analyzes and assesses their environmental effects, together with economic and social influences. Life cycle of a product is composed of five main stages, and Figure 3.2 illustrates this stages.

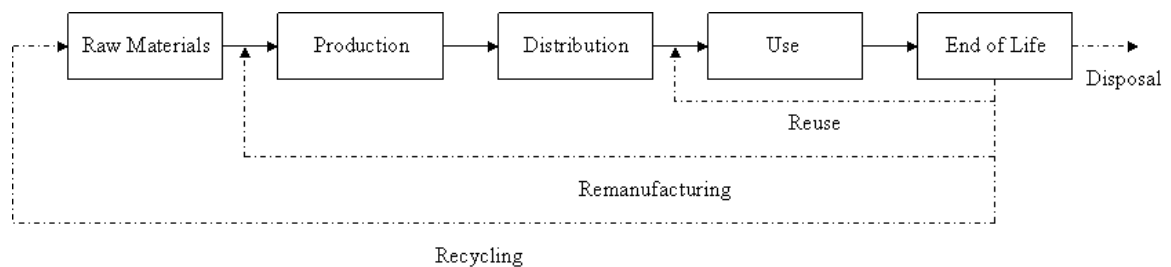


Figure 3.2. Product life cycle stages.

The stage of raw materials includes acquisition of resources, their delivery to production area, and their transformation into raw materials or energy. Raw materials and energy are produced from primary or virgin resources as well as from secondary or recycled resources. Delivered raw materials are stored in a production area, conveyed to the machinery, and processed into components which will be assembled for the completion of the final product. Storing the final product, packaging, and transportation are included in

the distribution stage. This stage entails not only energy consumption for transportation, but also resource consumption to produce the means of transport as well as storage facilities. Usage stage where the customer utilizes or consumes the product is the last stage before its end of life. In most cases, the utilization of goods further consumes additional resources and energy, and leaves behind refuse and waste. Furthermore, product can face with maintenance and servicing, repair of damages or damaged parts; or replacing obsolete parts. Finally, decisions are made after product is used and come to the end of life stage. At the end of life, there are several options for product termination. Product may be disposed, repaired and reused, remanufactured, and used in production again or recycled and returned to raw materials stage. Except disposal, all other options satisfy the cradle to cradle philosophy and form a close loop.

After identification of steps, inventory and cost analysis are performed with LCA and LCC tools which are previously described in Section 2.2.1 and 2.2.2., respectively. The aims of these analyses are to investigate the current status and to provide data for the proceeding phases. In the content of LCA, life cycle inventory analysis is carried out. All inputs including raw material consumptions and outputs such as emission amounts of the life cycle stages are listed. Similarly, costs are gathered from LCC analysis. The results obtained in this phase are fed into the following stages. More specifically, they are employed at the comparison of technical attributes part of the QFD and also at the data envelopment analysis.

### **3.2. Identification of Design Alternatives**

One of the most commonly applied customer-driven methodology in product planning and development field is quality function deployment (QFD). It is an overall concept that deploys customer requirements into product design by defining customer requirements and translating them to technical requirements. The main objective of using QFD is to fulfill customer expectations from the product and to improve the competitiveness against other products.

This enhanced quality function deployment based on life cycle thinking is constructed with following steps:

- Customer analysis and segmentation,
- Identification of customer requirements in each life cycle stage,
- Identification of technical attributes of the product,
- Construction of interrelationship matrix and correlation matrix,
- Generating design alternatives based on most important technical attributes,
- Comparison for technical attributes of design alternatives including product life cycle assessment of design alternatives,
- Comparison of customer satisfaction for design alternatives.

The traditional QFD explained in Section 2.2.3 is adjusted with life cycle thinking and incorporates different customer segmentation. The adjustments are directly applied to customer requirements part of the house of quality. Life cycle stages are integrated to QFD template for identifying the needs and expectations of customer from all life cycle stages, separately. Thus, critical ones for each life cycle stage are investigated and analyzed.

Accordingly, customer term is also modified in coherence with the sustainability notion and split into groups as external customer, internal customer, and society. External customers are the end users who buy and use the product whereas internal customers are the employees working at manufacturing, disassembly, recycling, and remanufacturing processes. Society is much broader concept and it includes everybody who is influenced by the product. The requirements of the customer profile consider the triple bottom line of sustainability that consists of environment, society, and economy. These aspects are embodied in the listed requirements of each customer's life cycle stages.

<i>Customer Requirements</i>		Ex. Cust.	Int. Cust.	Society
Raw Mat	...	X	X	X
	...	X	X	
	...	X		X
	...			X
Production	...	X		
	...	X		
	...	X		
	...	X		
Distribution	...	X		
	...	X	X	X
	...	X		X
	...	X		
Usage	...		X	
	...		X	
	...		X	
End of Life	...			X
	...			X
	...			X
	...			X

Figure 3.3. Customer requirements structure of enhanced QFD.

As mentioned above, the customer requirements component is divided into two parts which are life cycle stages and customer types. It provides the response to question “What are the requirements of  $x$  in  $y$  stage?”. The symbol of  $x$  denotes the aforementioned three customer segments, and  $y$  refers to life cycle stages, namely raw materials, production, distribution, usage, and end of life. In some circumstances, the customer needs and expectations can be the same for a specific life cycle stage for different segments. In order to avoid requirement replications, the responses to these questions are organized in a matrix structure. Rows are the parts of life cycle stages, and columns designate if the specific requirement is appropriate for each customer type. All requirements are marked once in rows part, and the owner/owners are selected from the columns. The structure of customer requirements part of the enhanced QFD model is displayed in Figure 3.3 and described more explicitly in the following.

The needs and expectations of external customer are listed in Table 3.1 as a template. For the generic structure, the multidimensional definition of product quality is reflected into the usage stage as specified by Garvin (1988). Additional features are included for the other stages. These are very general concepts and can be more diversified according to specific product.

Table 3.1. The external customer's requirements.

	<i>External Customer Requirements</i>
<i>Raw Materials</i>	Safety
<i>Production</i>	-
<i>Distribution</i>	Deliverability
<i>Usage</i>	Performance Features Reliability Conformance Durability Serviceability Aesthetics Perceived Quality
<i>End of Life</i>	Reversibility

According to Garvin's quality definition, performance refers to the fundamental functionality. In addition to primary characteristics, customer also seeks extra attributes that make the product more attractive. These characteristics are defined in product features. There are three time related dimensions of product quality. Reliability is defined as the survival probability. It is desired not to have any unexpected failures during the economic lifetime of the product. Durability is a quality dimension which reflects the length of the economic lifetime. Serviceability is the third dimension about the ease and speed of putting the product back into operation. It covers a lot of issues such as the ease of access to the access to the service network, availability of spare parts and competence of repair personnel. Moreover, conformance quality is the agreement of manufactured product with the design specifications. The aesthetics dimension is any feature which appeals to our senses. Finally, perceived quality is related to the brand name and the company image.

As it is indicated, the requirements of external customer are mainly focused on usage stage since this type of customer acts only as the buyer and user of the product. However, there are also some exceptions in the other stages, since they are implicitly related to usage stage. For instance, product safety is highly correlated with raw materials. Deliverability is the expectation of finding the product in the market when it is demanded. Additionally, external customer is the one who brings the product to end of life, and at this point several requirements such as appropriate reverse logistics points to collect product back occurs, and they are connected with the reversibility concept.

As summarized in Table 3.2, the internal customer requirements are related to working conditions and ease of work. The primary need is about health and safety problems. Minimum or non-existing adverse conditions in health and safety issues are necessities of all life cycle stages. Since product is formed in a system and suppliers are included in this system, the working conditions of suppliers and subcontract companies also require attention. Moreover, in the concept of sustainability, working conditions comprise the conformance to legislations such as health and safety regulations, equality of workers, and the properties of workers.

Table 3.2. The internal customer's requirements.

	<i>Internal Customer Requirements</i>
<i>Raw Materials</i>	Minimum adverse health/safety impacts of raw materials Easy to process
<i>Production</i>	Improved employee conditions such as health/safety, equality, child labors etc. at company and subcontract company Easy to manufacture, assemble and disassemble
<i>Distribution</i>	Easy to package
<i>Usage</i>	Ease for repair and maintenance
<i>End of Life</i>	Easy to sort Ease for repair Ease of disassembling, remanufacturing, recycling, reuse, and disposal Minimum adverse health/safety impacts of end of life options

Ease of work requirements differs based on how the employee is included in life cycle stages. In raw materials stage, employees demand the material which is the easiest

way to process. Afterwards, ease of production is required. Practical manufacturing systems can be achieved by automation, reducing or totally eliminating the human intervention. Packaging works related to distribution are needed to be as simple as possible in terms of formation and time consumption. After the product is sold, the role of employees do not end rather continue for maintenance. At the end of life, the options are needed to be analyzed, and according to these options, the product is disassembled; the parts of the product may be reused, recycled or remanufactured.

The society is another segment of the customer profile. Every product may have considerable impact on our world, besides its effect on the internal and external customers. Therefore, society aims to minimize these negative effects on the environment. The requirements are generally composed of design for environmental strategies. Dematerialization is the concept of using less material and less resources of the world. It is achieved through product by reducing or miniaturizing components and thickness. The impact degree of raw materials due to extraction, processing and transportation changes in accordance with the kind of material. Being hazardous, toxic, renewable, recyclable properties are strictly correlated with the material type, and these factors are needed to be considered in material selection.

At the production stage, clean processes and production technologies are significant needs and expectations that should be deeply considered. Adopting innovative and environmental conscious technologies to the production facilities provides less emission, effluents, wastes and energy usage, and effectiveness projects reduce wastes and energy usages. As a result, these kinds of non-negative impacts on environment also influence local community in a positive manner.

Packaging wastes, emissions and negative impacts are detected in distribution stage of the life cycle. In order to minimize them, modes of transportation and fuel usage are needed to be optimized. The proper usage style of the product is required by users at product usage. Design of the product should be convenient to less energy consumption during the usage. The wastes such as radiation can also come out in the usage phase. Therefore, the design should also satisfy the need of less waste in the usage. At the last

stage of life cycle, designers should consider the end of life options and choose one of them in the early design phase. This optimal choice should have the minimum negative environmental and social effects and maximum economical gain.

Table 3.3. The society's requirements.

	<i>Society Requirements</i>
<i>Raw Materials</i>	Less resource usage /Dematerialization Less of non-renewable materials Less hazardous & toxic materials Ease of recovery, reuse, recycling Ease of extraction and processing of raw materials Ease of transportation from supplier
<i>Production</i>	Clean processes and production technology Less emissions to air Minimum effluents Minimum waste Minimum energy usage More local investments Positive impacts on local community
<i>Distribution</i>	Less packaging, volume, weight Less emissions to air Less waste
<i>Usage</i>	Proper usage style of the product Less waste from product Less energy consumption
<i>End of Life</i>	The choice of optimum end of life option with minimum environmental and social effects and maximum economical gain

Apart from customer segmentation and identifying their life cycle requirements, the rest of the QFD methodology follows the same steps with traditional QFD in constructing HOQ. The design alternatives are formed in accordance with the crucial technical attributes, and then assessed in the comparison component of the HOQ. Comparison is divided into two parts according to the technical attributes and customer satisfaction. In technical comparison, LCA and LCC results are used for assessment of product design options. Additionally, in comparison of customer satisfaction, each design option is assessed in different tables illustrating the satisfaction level of each requirement for calculating a total satisfaction rate. As a consequence of this phase, key performance indicator values are prepared to be input to the data envelopment model.

### 3.3. Optimal Design Selection

The third phase of the proposed methodology is the selection of the most sustainable design option from the alternatives assessed in “Identification of Design Alternatives” phase. In this phase of the methodology, there are three more steps as:

- Model construction,
- Model execution,
- Interpretation.

The optimal design selection is fulfilled with data envelopment analysis which is a linear programming approach for measuring the relative performance of Decision Making Units (DMUs). The reason of applying a mathematical model is the existence of multiple inputs and outputs which makes comparisons complicated in the evaluation process. Besides, DEA is widely applied in managerial issues as a performance measuring decision making tool due to its usefulness in evaluating multi-criterion systems and providing improvement targets for these systems.

DMU is defined as the entity which is responsible for the conversion of inputs into outputs, and whose performance is the object of assessment (Cooper et al., 2000). It represents business operations or processes that are going to be assessed in DEA. For each DMU, crucial inputs and outputs are selected which are relevant to performance. All DMUs must have the same input and output types which are nonnegative valued data. Moreover, measurement units of different inputs and outputs are not required to be identical.

Efficiency of a DMU is basically the ratio of outputs to inputs. DEA calculates this efficiency by assigning weights to inputs and outputs, and evaluates the ratio of linear combination of inputs to linear combination of outputs as in Equation (3.1).

$$Efficiency = \frac{Weighted\ Sum\ of\ Outputs}{Weighted\ Sum\ of\ Inputs} \quad (3.1)$$

The efficient frontier is a series of points, a line or a surface connecting the most efficient DMUs that are determined according to their inputs and outputs. Efficient frontier is also called data envelope. The frontier is drawn by connecting the efficient DMUs, so inefficient DMUs are enveloped within the line. The DMUs lying on the efficient frontier are called efficient, whereas others that do not lie are called inefficient. The data envelope cannot be efficiently shown in the graph when the number of inputs and outputs exceed a limit, since maximum three dimensional graphs are possible.

The region determined by the efficient frontiers is called production possibility set (PPS) and the DMUs on the frontiers constitute reference set. If an increase in inputs results with increase in outputs with a same proportion, the system is called constant returns to scale (CRS). In this system, for every unit increase in the input that enters to the process, the output produced increases by a constant proportional quantity. If an increase in inputs results with increase in outputs with a different proportion, the system is called variable returns to scale (VRS) or increasing returns to scale (IRS) /decreasing returns to scale (DRS).

Moreover, orientations of DEA are in two types which are input oriented and output oriented models. Input oriented model focuses on achieving efficiency through the proportional reduction of inputs while outputs are kept constant. It aims to minimize inputs while satisfying minimum output levels. On the other hand, output oriented model attempts to maximize outputs without requiring more of any of the observed input values. The efficiency scores, efficient and inefficient DMU sets, and projected points based on output maximization are equal to the input minimization in the case of constant returns to scale. When the problem is variable returns to scale, even though the efficient and inefficient DMU sets are identical in input and output oriented models, the efficiency scores and projected points differ.

### **3.3.1. The Basic Data Envelopment Analysis Model**

The basic data envelopment analysis model finds the efficiency by getting a ratio of linear combination of inputs and linear combination of outputs. As an example, there are s

number of DMUs which have  $m$  inputs and  $n$  outputs. Inputs are denoted by  $x_{ij}$  as the  $i$ th input for the  $j$ th DMU,  $i = 1, 2, \dots, m$  and  $j = 1, 2, \dots, s$ ; whereas outputs are denoted by  $y_{kj}$  the  $k$ th output for the  $j$ th DMU,  $k = 1, 2, \dots, n$  and  $j = 1, 2, \dots, s$ . The weights are defined as  $v_i$  the associated weight for the  $i$ th input,  $i = 1, 2, \dots, m$  and  $u_k$  the associated weight for the  $k$ th output,  $k = 1, 2, \dots, n$ . Efficiency score of DMU <sub>$j$</sub> ,  $E_j$ , is calculated as in Equation (3.2).

$$E_j = \frac{u_1.y_{1j} + u_2.y_{2j} + \dots + u_n.y_{nj}}{v_1.x_{1j} + v_2.x_{2j} + \dots + v_m.x_{mj}} \quad (3.2)$$

Each DMU selects weights such that it maximizes its own efficiency, subject to constraints that ensure:

- i. No units can have an efficiency score greater than 1 and less than 0
- ii. Every weight must be strictly greater than 0

When  $E_j$  is calculated as 1, DMU <sub>$j$</sub>  is called “efficient”. For the DMUs with efficiency score less than one have less performance, and they are called “inefficient”. A complete DEA calculates  $s$  number of efficiencies by solving  $s$  number of models (Adler et al., 2002). In each calculation, the model maximizes the efficiency of DMU under evaluation by taking the appropriate weight values. Thus, if a DMU is found as inefficient despite this flexible weight choice, it can be strongly claimed that it is inefficient.

There exist various models of DEA which use different ways in measuring efficiency. The most well-known DEA models are CCR model (Charnes et al. 1978), and BCC model (Banker et al. 1984).

3.3.1.1. CCR Model. A fractional programming model known as the CCR model was developed by Charnes, Cooper and Rhodes (1978) to determine the efficiency score of each of the DMUs in a data set of comparable units. CCR is based on constant returns to scale. The model determines the best set of weights for each DMU when the problem is solved for each DMU under consideration.

Data envelopment model for  $DMU_{j_0}$  is constructed as in Equation (3.3). In the input oriented version, the objective function maximizes the efficiency of the DMU using the weights  $u_k$  and  $v_i$  for the outputs and the inputs, respectively. The weights are determined by the model such that the efficiency score of the DMU under consideration is maximum and when the same set of weights are applied to the other DMUs in the sample, their efficiency score cannot exceed one. The CCR model provides a global view for all the DMUs with a consistent standard for comparison. The efficiency obtained by the CCR model is generally regarded as the “productive efficiency”.

$$\begin{aligned} & \text{Maximize} \quad \frac{\sum_k u_k \cdot y_{kj_0}}{\sum_i v_i \cdot x_{ij_0}} \\ & \text{Subject to} \quad \frac{\sum_k u_k \cdot y_{kj_0}}{\sum_i v_i \cdot x_{ij_0}} \leq 1 \quad \forall j \end{aligned} \quad (3.3)$$

One problem with the above formulation is that it has an infinite number of solutions. Therefore, in order to have a unique solution, the following additional constraint in Equation (3.4) can be imposed to the formulation in (3.3):

$$\sum_i v_i \cdot x_{ij_0} = 1 \quad (3.4)$$

Thus, fractional DEA model is transformed to linear model in order to avoid non-linearity. This form, (3.4), is known as the multiplier form of DEA which can be solved for each  $DMU_j$  ( $j=1,2,\dots,s$ ) for obtaining relative efficiency of the same.  $DMU_j$  is inefficient if optimal value of its efficiency score is less than 1. The formulation (3.5) is a linear

programming model considering input oriented whereas the formulation (3.6) below is output oriented.

The dual form is also used in many studies, since the number of constraints is decreased in dual problem. In dual formulation,  $\theta$  is the relative efficiency of DMU  $j$ . Both primal and dual models provide the same solution by using the same data. The dual model is obtained by assigning a dual variable to each constraint in primal model. In this case, when primal model has  $m+n$  number of variables, and  $m+n+s+1$  number of constraints; the dual model has only  $n+m$  number of constraints. The dual formulations are presented in (3.7) and (3.8).

Table 3.4. CCR models.

Primal Input Oriented CCR Model	Primal Output Oriented CCR Model
$\begin{aligned} \text{Max. } & \sum_{k=1}^s u_k \cdot y_{kj_0} \\ \text{St. to } & \sum_{i=1}^m v_i \cdot x_{ij_0} = 1 \\ & \sum_{k=1}^s u_k \cdot y_{kj} - \sum_{i=1}^m v_i \cdot x_{ij} \leq 0 \quad \forall j \\ & u_k, v_i \geq 0 \end{aligned} \quad (3.5)$	$\begin{aligned} \text{Min. } & \sum_{i=1}^m v_i \cdot x_{ij_0} \\ \text{St. to } & \sum_{k=1}^s u_k \cdot y_{kj_0} = 1 \\ & \sum_{k=1}^s u_k \cdot y_{kj} - \sum_{i=1}^m v_i \cdot x_{ij} \leq 0 \quad \forall j \\ & u_k, v_i \geq 0 \end{aligned} \quad (3.6)$
Dual Input Oriented CCR Model	Dual Output Oriented CCR Model
$\begin{aligned} \text{Min. } & \theta \\ \text{St. to } & \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq \theta \cdot x_{ij_0} \quad \forall i \\ & \sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad \forall k \\ & \lambda_j \geq 0 \\ & \theta \text{ unrestricted} \end{aligned} \quad (3.7)$	$\begin{aligned} \text{Max. } & \theta \\ \text{St. to } & \theta \cdot y_{kj_0} - \sum_{j=1}^n \lambda_j \cdot y_{kj} \leq 0 \quad \forall k \\ & \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad \forall i \\ & \lambda_j \geq 0 \\ & \theta \text{ unrestricted} \end{aligned} \quad (3.8)$

3.3.1.2. BCC Model. Different from the CCR model, the BCC model with VRS feature has its frontier spanned by the convex hull of the existing DMUs (Cooper *et al.*, 2000). Compared to the CCR model, DMUs can obtain better efficiency scores under the BCC model due to the more conservative frontier. Distinguishing from the CCR efficiency, the BCC efficiency is generally taken as the technical efficiency.

The BCC version of the DEA model is in common use like the CCR model. The primary difference between the CCR and the BCC formulations is the treatment of returns to scale. The CCR model is based on constant returns to scale, whereas the BCC model is more flexible and allows variable returns to scale. The only difference of dual BCC models from dual CCR models is an additional  $\sum_{j=1}^n \lambda_j = 1$  constraint. This equation together with non-negativity constraint enables convexity condition.

Table 3.5. BCC models.

Primal Input Oriented BCC Model	Primal Output Oriented BCC Model
$\text{Max. } \sum_{k=1}^s u_k \cdot y_{kj_0} + q_0$ $\text{St. to } \sum_{i=1}^m v_i \cdot x_{ij_0} = 1$ $\sum_{k=1}^s u_k \cdot y_{kj} - \sum_{i=1}^m v_i \cdot x_{ij} + q_0 \leq 0 \quad \forall j$ $u_k, v_i \geq 0$ $q_0 \text{ unrestricted} \quad (3.9)$	$\text{Min. } \sum_{i=1}^m v_i \cdot x_{ij_0} + w_0$ $\text{St. to } \sum_{k=1}^s u_k \cdot y_{kj_0} = 1$ $\sum_{i=1}^m v_i \cdot x_{ij} - \sum_{k=1}^s u_k \cdot y_{kj} + w_0 \geq 0 \quad \forall j$ $u_k, v_i \geq 0$ $w_0 \text{ unrestricted} \quad (3.10)$
Dual Input Oriented BCC Model	Dual Output Oriented BCC Model
$\text{Min. } \theta$ $\text{St. to } \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq \theta \cdot x_{ij_0} \quad \forall i$ $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad \forall k$ $\sum_{j=1}^n \lambda_j = 1$ $\lambda_j \geq 0$ $\theta \text{ unrestricted} \quad (3.11)$	$\text{Max. } \theta$ $\text{St. to } \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad \forall i$ $-\sum_{j=1}^n \lambda_j \cdot y_{kj} + \theta \cdot y_{kj_0} \leq 0 \quad \forall k$ $\sum_{j=1}^n \lambda_j = 1$ $\lambda_j \geq 0,$ $\theta \text{ unrestricted} \quad (3.12)$

### 3.3.2. Environmental Data Envelopment Analysis

As environmental issues gain importance, DEA literature has changed and environmental efficiency concept is developed. Environmental DEA differs from traditional DEA models, since it divides outputs to groups as desired and undesired.

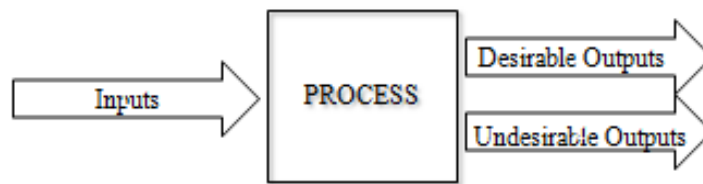


Figure 3.4. Environmental production system.

In this division illustrated in Figure 3.4, outputs like emissions are in class of undesired outputs, and they are treated differently from the desired ones. The production system produces both desired outputs and undesired outputs with same inputs.

3.3.2.1. Environmental Data Envelopment Analysis Approaches. Many recent studies are devoted to model undesirable factors in DEA. The pioneering studies of environmental data envelopment models transform undesirable outputs to a monotone decreasing function and consider them with desired outputs. In this way, by maximizing the transformed values, the original undesirable output values are minimized. The most acceptable transformation presented in formulation (3.13) which is suggested by Koopmans (1951). In this transformation, undesirable outputs are like desirable outputs, and successfully integrated to the model. However, the efficiency may be found less than zero due to the negativity of the function.

$$f(U) = -U \quad (3.13)$$

In order to avoid negativity, a different transformation is defined as in Equation (3.14) (Ali and Seiford, 1990; Scheel, 2001; Seiford and Zhu, 2002). This approach guarantees positive efficiency values, but it causes dependency to  $\beta$ .

$$f(U) = -U + \beta \quad (3.14)$$

Another transformation is the multiplicative inverse which is (Lovell et al., 1995). Formulation (3.15) is regarded as more complicated than other transformation methods.

$$f(U) = 1/U \quad (3.15)$$

Since there are many transformation types, selection of a suitable transformation depends on the case. The improperly selected approaches based on data transformation may unexpectedly produce adverse results.

Moreover, undesirable outputs can be directly included in DEA without any transformation by modifying the assumptions of the model. Accordingly, direct approach and following assumptions are taken into account in this study. Assume  $x \in R_+^I$ ,  $y \in R_+^K$ ,  $b \in R_+^L$  be the vectors of inputs, desirable and undesirable outputs, respectively. The production technology is characterized by the output set (Chung et al., 1997).

$$P(x) = \{(y, b); x \text{ can produce } (y, b)\}$$

$P(x)$  is defined as environmental output set and holds the following assumptions:

- Weak disposability of outputs: This assumption assures that both the desirable and the undesirable outputs can be disposed proportionally. It also implies that it is not possible to reduce only the undesirable outputs while keeping the inputs and the desirable outputs constant.

$$\text{If } (y, b) \in P(x) \text{ and } 0 \leq \theta \leq 1, \text{ then } (\theta y, \theta b) \in P(x)$$

- Null-jointness: The only way to eliminate all undesirable outputs is to stop production process, since it is technically impossible to produce only desirable outputs without producing any of undesirable outputs.

$$\text{If } (y, b) \in P(x) \text{ and } b = 0, \text{ then } y = 0$$

- Closeness of the set:  $P(x)$  is a close set, including all points on the frontiers.
- Freely or strongly disposable inputs: Amount of inputs can be increased without an increase in outputs. If amount of  $y + b$  can be produced from  $x$ , then  $y + b$  can also be produced from any  $x'$  that implies  $x' \geq x$ .
- Freely or strongly disposable desirable outputs: A specific amount of desirable output  $y$  can be produced from  $x$ , and for any amount  $y'$  that implies  $y' \leq y$  can also be produced from  $x$ .

All of these assumptions designed for direct approach of environmental data envelopment analysis are adopted in the model of proposed methodology which is explained in the following section. Null-jointness and closeness of the set are the basic assumptions, and the weak disposability property is the fundamental element of the model.

3.3.2.2. Environmental Data Envelopment Analysis Model. The third phase of the proposed methodology constructs and executes environmental DEA model based on direct approach and its assumptions in selection of the most sustainable design option. In the environmental data envelopment analysis, decision making units (DMUs) are selected as design alternatives. The linear mathematical model of DEA aims to detect the most sustainable design option. Inputs and outputs are selected from the crucial aspects of sustainability which are already considered by other methodologies in the previous sections.

The environmental data envelopment model gathers all other tools of proposed methodology in its framework and provides a result to our selection problem. Data are taken from comparison of technical attributes part of the QFD and comparison of customer satisfaction applied in the second phase of the methodology. Raw materials and emissions are specified with life cycle assessment and cost values are taken from life cycle costing

analyzed in first and second phases. According to the formulation and other phases of the proposed methodology, inputs refer raw materials and costs, undesired outputs are emissions, desired outputs are customer satisfaction levels.

In this study, the environmental DEA approach which exhibits constant returns to scale (CRS) as proposed by Färe et al. (1989) is employed. It is assumed that there are  $j$  amount of DMUs and the one which is going to be assessed is symbolized as  $j_0$ . The observed data for each  $DMU_j$  which are input, desirable output, and undesirable output are respectively  $x_{ij}$ ,  $y_{kj}$ , and  $b_{lj}$ . Weak disposal production technology set is defined as:

$$P^w(x) = \left\{ \begin{array}{l} (y, b): \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad i = 1, 2, \dots, m \\ \sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad k = 1, 2, \dots, s \\ \sum_{j=1}^n \lambda_j \cdot b_{lj} = \theta \cdot b_{lj_0} \quad l = 1, 2, \dots, p \end{array} \right\} \quad (3.16)$$

Additionally, this reference set can also be modified with strong disposability property as:

$$P^s(x) = \left\{ \begin{array}{l} (y, b): \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad i = 1, 2, \dots, m \\ \sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad k = 1, 2, \dots, s \\ \sum_{j=1}^n \lambda_j \cdot b_{lj} \geq \theta \cdot b_{lj_0} \quad l = 1, 2, \dots, p \end{array} \right\} \quad (3.17)$$

The reference sets are illustrated in Figure 3.5. The intensity vector  $\lambda$  serves to construct convex combinations of the observed inputs and outputs, forming a feasible polytope with facets connecting the observed points. The inequality  $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0}$  allows feasible vertical extensions south of the polytope, reflecting strong disposability of the desirable outputs. The equality  $\sum_{j=1}^n \lambda_j \cdot b_{lj} = \theta \cdot b_{lj_0}$  allows feasible radial contractions of the polytope to the origin, reflecting weak disposability of the undesirable outputs. The output set  $P^w(x)$  is the region OABCDE. On the other hand, the constraint  $\sum_{j=1}^n \lambda_j \cdot b_{lj} \geq \theta \cdot b_{lj_0}$  mentioned in formulation (3.17) allows strong disposability of

undesirable outputs, so that in Figure 3.5 the output set  $P^s(x)$  is the region OFBCDE. The region OFBA represents production possibilities that are feasible under strong disposability of all outputs, but not feasible under weak disposability of undesirable outputs (Färe et al., 1989).

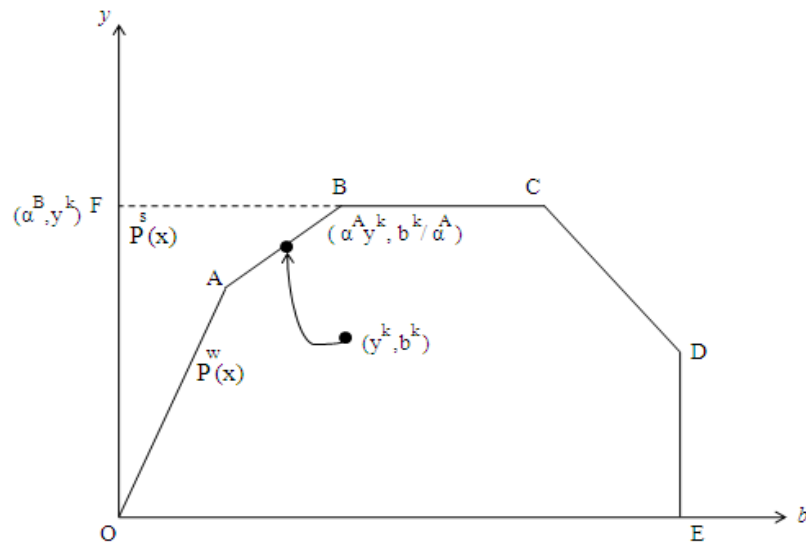


Figure 3.5. Productions sets of  $P^w(x)$  and  $P^s(x)$ .

The models based on aforementioned reference sets are also applied and developed by Tyteca (1997), Zhou et al. (2007, 2008a, 2008b), Zaim (2004), Kuosmanen and Kortelainen (2004). In this study, these models are diversified in the means of input – output oriented and CCR- BCC. The models which are going to be used for obtaining environmental efficiency scores are summarized Table 3.6. In our case,  $DMU_{j_0}$  is the design alternative which is investigated.  $DMU_j$  are the other design options.

In the case study, the data of environmental data envelopment models are analyzed in Sections 4.4.8 and 4.4.9, and the results are illustrated in Section 4.5. The model is solved for each  $j$ . Notations in these formulations are listed as:

$\theta$  : Dual efficiency score of  $DMU_{j_0}$

$\lambda_j$  : Dual weight variable of  $DMU_j$

- $x_{1j_0}$ : The total cost of  $DMU_{j_0}$   
 $x_{2j_0}$ : The raw material consumption amount of  $DMU_{j_0}$   
 $y_{1j_0}$ : The external customer satisfaction of  $DMU_{j_0}$   
 $y_{2j_0}$ : The internal customer satisfaction of  $DMU_{j_0}$   
 $y_{3j_0}$ : The society satisfaction of  $DMU_{j_0}$   
 $b_{1j_0}$ : The emission amount of  $DMU_{j_0}$

Table 3.6. Environmental data envelopment models

Dual Input Oriented CCR Model	Dual Output Oriented CCR Model
$Min. \theta$ $St. to \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad \forall i$ $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad \forall k$ $\sum_{j=1}^n \lambda_j \cdot b_{lj} = \theta \cdot b_{lj_0} \quad \forall l$ $\lambda_j \geq 0 \quad \forall j$ $\theta \text{ unrestricted} \quad (3.18)$	$Max. \theta$ $St. to \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq \theta \cdot x_{ij_0} \quad \forall i$ $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq \theta \cdot y_{kj_0} \quad \forall k$ $\sum_{j=1}^n \lambda_j \cdot b_{lj} = b_{lj_0} \quad \forall l$ $\lambda_j \geq 0 \quad \forall j$ $\theta \text{ unrestricted} \quad (3.20)$
Dual Input Oriented BCC Model	Dual Output Oriented BCC Model
$Min. \theta$ $St. to \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq x_{ij_0} \quad \forall i$ $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq y_{kj_0} \quad \forall k$ $\sum_{j=1}^n \lambda_j \cdot b_{lj} = \theta \cdot b_{lj_0} \quad \forall l$ $\sum_{j=1}^n \lambda_j = 1$ $\lambda_j \geq 0 \quad \forall j$ $\theta \text{ unrestricted} \quad (3.19)$	$Max. \theta$ $St. to \sum_{j=1}^n \lambda_j \cdot x_{ij} \leq \theta \cdot x_{ij_0} \quad \forall i$ $\sum_{j=1}^n \lambda_j \cdot y_{kj} \geq \theta \cdot y_{kj_0} \quad \forall k$ $\sum_{j=1}^n \lambda_j \cdot b_{lj} = b_{lj_0} \quad \forall l$ $\sum_{j=1}^n \lambda_j = 1$ $\lambda_j \geq 0 \quad \forall j$ $\theta \text{ unrestricted} \quad (3.21)$

## **4. THE CASE STUDY**

The proposed methodology illustrated in the preceding chapter is implemented for evaluating design options of beverage containers and selection of the best alternative considering trade-offs in sustainability dimensions. First of all, the life cycle stages of glass beverage containers are presented. Afterwards, life cycle inventory analysis and life cycle costing are carried out. Design alternatives and their specifications are constructed and analyzed by means of quality function deployment methodology. Finally, the most sustainable design option is selected through data envelopment analysis.

### **4.1. Life Cycle of Glass Containers**

The life cycle stages of beverage containers are introduced as the first phase of the proposed methodology. Since the life cycle thinking is adopted as the governing philosophy in the methodology, a brief background knowledge of the beverage container system would be beneficial for the implementation of the case study.

#### **4.1.1. Raw Materials**

The raw materials of the glass are natural and obtained from the environment. The six main ingredients of glass are sand ( $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ ), soda ash ( $\text{Na}_2\text{O}$ ), limestone ( $\text{CaCO}_3$ ), dolomite ( $\text{CaO}$  and  $\text{MgO}$ ), feldspar, and perlite ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$  and  $\text{CaO}$ ). Additionally, sometimes sodium sulfate is used as an ancillary substance.

Moreover, the color of the glass is obtained with specific ingredients. For instance, pyrite, anthracite, sulphur, and chromite are these kinds of components giving color. Similarly, in order to get a colorless glass, specific materials such as ceriumoxide, zinc selenite and cobaltoxide are required.

Additionally, another important ingredient of glass is cullet which is the name of crushed glasses with the aim of recycling. After all, the glass is one of the most sustainable materials in the world as it can be endlessly used in production of new glasses. Cullet usage reduces the amount of other raw materials and supports less raw material consumption.

#### 4.1.2. Production

Glass production is a continuous process. Once the glass is melt, the processes never stop, and glass is produced continuously. There are seven main steps for manufacturing as displayed in Figure 4.1.

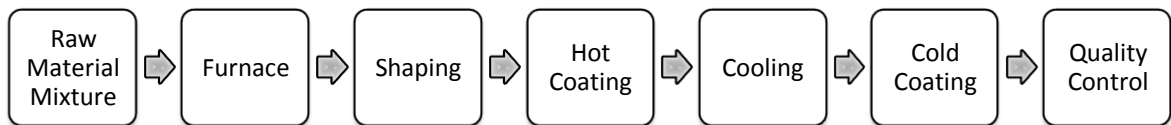


Figure 4.1. Production process of glass.

The first step of the production is to create a homogeneous mixture of each raw material according to desired glass composition. After the mixture is prepared, it is transferred to the furnace which melts at 1500 - 1600 C°. Then, the melted glass passes from forehearth and strokes as drops of specific mass. The drops of melted glass are shaped by blowing air, to form bottle.

The surfaces of the glass containers are coated with a chemical to protect the surface. Elimination of bubbles and the homogenization of the mass of glass are enabled by hot coating. This process is carried out under high temperature before the containers are cooled. Additionally, a cold coating is also applied with the purpose of protecting the surface of containers from scratches. Since glass is a very fragile material, it should be cooled gradually to decrease inner tension. This controlled and partial heating/cooling is also termed as annealing.

Following to production, various tests are applied to control the quality of containers. Containers that fail any of the tests are automatically separated. These manufacturing scraps are used as process cullet and return to raw material mixture again for producing new containers. Containers that pass the quality tests are dispatched to packaging.

#### **4.1.3. Distribution**

Distribution is one of the most crucial part of the system as a linkage process among life cycle stages. The logistics activities of the supply chain management and reverse supply chain are considered in the distribution stage.

In accordance with the supply chain dynamics, product is transported from production facility to filling facility, from filling facility to distribution centers, from distribution centers to sale points, and from sale points to consumers' location. The reverse is performed when the product usage terminates. In the reverse supply chain, empty container is carried from consumers' location to collection centers or garbage, and from collection centers to recycling facilities or filling facilities.

#### **4.1.4. Filling Operation and Usage**

As a packaging material, glass has some advantages and drawbacks. Firstly, it is one of the most preferred packaging material for storing food and drinks since it is impermeable and does not affect the taste. It has high resistance against chemical materials, corrosion and radiation. Additionally, it is rigid so that it does not change shape and dimensions. Besides, glass is very convenient for recycling and reusing. The raw materials of the glass are derived from the environment, and this property provides glass to be cheap. As for the disadvantages of glass, it is unsuitable for products that are damaged by the sunlight. Moreover, glass is heavier than other packaging materials and breaks easily unless toughened. Lastly, the production is very energy intensive and damages environment.

The glass containers have two usage alternatives: one-way and multi-way. One-way containers are used one time whereas multi-way containers are used more than one time. Multi-way containers are the containers which include deposit in the purchasing price. In this application, when customers return the containers after usage, deposit amount is given back. The policy of multi-way containers is voluntary and may be applied according to the filling facilities' strategies.

The number of reusing the same bottle is called trippage rate in deposit systems. Although in this study it is assumed as 5 in all deposit scenarios, defining a specific value is very complicated in real life. A container can be taken out of circulation because of breakage, scuffing, or contamination. Scuff marks on refillable bottles are made by the washing, filling, and bottle-handling machinery. Contamination may come from improper use of the bottle such as filling it with paint thinner or with another toxic liquid. Containers also come out of circulation when they are not returned. Trippage rate depends on the return rate, the percentage of containers that are returned. High return rates are indicators of an effective multi-way system, a system in which empty containers are returned from the consumer to the bottling plant, and in which deposits and refunds are exchanged between the bottler and the seller, and between the seller and the consumer.

Once containers are brought to the filling facility, cleaning and filling operations are held. Initially, returned multi-way containers are uncased and conveyed to inspectors who manually remove uncleanable and damaged containers from the line. The remaining containers are transferred to the bottle washing unit. The bottle washing process takes places in a series of stages. As the first step, the containers are pre-rinsed by jetting with warm reclaimed water. The dirty containers go through soaking in compartments filled with caustic solution. Following to the caustic compartment, the containers are washed in a hot water compartment which removes most of the caustic solution from containers. Finally, the containers are rinsed in three stages which are secondary reclaim water rinsing, primary reclaim water rinsing, and fresh water rinsing. On the other hand, cleaning process of one-way containers is simpler than multi-way containers as having only rinsing operations. When all containers are cleaned, they are filled with beverage and packaged.

The finished products are stocked and dispatched to distribution centers in the distribution stage of the life cycle.

#### 4.1.5. End of Life

End of life options of the glass containers differ according to cases of usage. In the best case of multi-way containers, customer uses the product and returns it to the collection points such as supermarkets. These products are cleaned and refilled. On the other hand, if the customer does not return the product, it mostly goes to disposal, and it can rarely be selected for recycling or deposit.

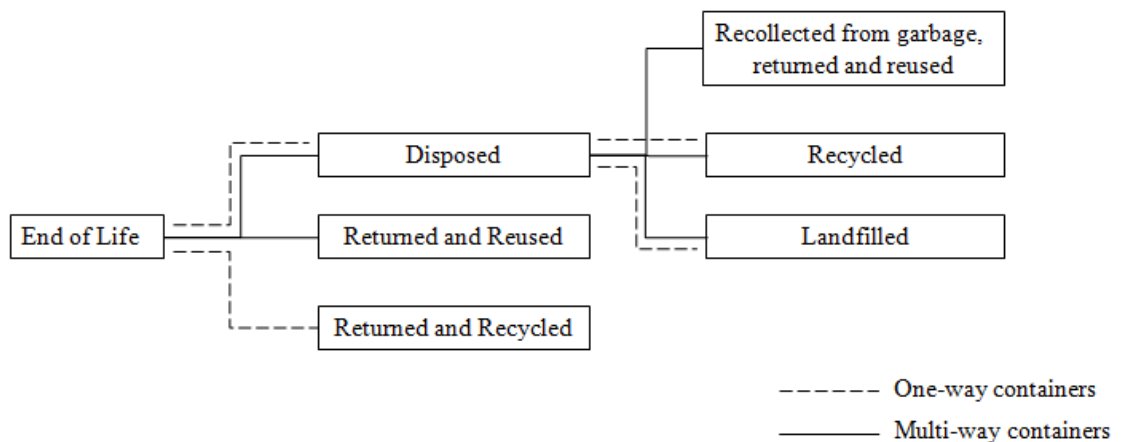


Figure 4.2. End of life options for glass containers.

In the case of one-way containers, the roadmap is similar to multi-way containers except reusing. The best case is the return of the product to the collection points (e.g. recycling boxes) for gathering, reprocessing and recycling, respectively. If the product is thrown into garbage, it mostly goes to disposal and it can rarely be selected for recycling.

4.1.5.1. Recycling. The responsibility of collecting glass waste from collection points belongs to city municipalities and district municipalities. Municipalities are obliged to prepare a packaging waste management plan in order to ensure separate collection at the source of packaging wastes. Gathered glasses are then sold to cullet facilities which prepare them for recycling. Cullet is the name of glass broken in little pieces, and making cullet is necessary before recycling.

Recycling is promoted by the government through regulations. Recycling targets are specified every year, and inspections are conducted in all over the world. Glass recycling targets of Turkey are indicated in Table 4.1 according to “Regulation on the Control of Packaging Waste” published in Turkish Official Journal in 24 July 2007 (The Ministry of Environment and Forestry, 2007). For this year, 38% glass recycling is set as target which is actually a low recycling rate when it is compared with 60% recycling target of “European Union Packaging Directive” (European Parliament and Council, 2010).

Table 4.1. Recycling targets of glass in Turkey.

Years	2005	2006	2007	2008	2009	2010	2011	2012
Targets (%)	32	33	35	35	36	37	38	40
Years	2013	2014	2015	2016	2017	2018	2019	2020
Targets (%)	42	44	48	52	54	56	58	60

There are numerous and substantially important environmental benefits of recycling. First of all, glass is sustainable and 100% recyclable. Thus, it can be recycled repeatedly with no loss of purity or quality in the glass. By recycling, virgin resource consumption reduces. The energy needed to melt recycled glass is 30% less than the needed energy to melt raw materials used to make new containers. Hence, lower energy is consumed in production with recycled content compared to the production with natural resources. Additionally, pollution and emissions are decreased by reduced energy and raw material consumption. Furthermore, since glass is produced from natural materials such as sand and limestone and has a low rate of chemical interaction in its contents, glass recycling is useful, and glass can be safely reused. Recycling of glass is simple compared to other

materials. It is accepted by almost all curbside recycling programs and municipal recycling centers. Economical advantages of recycling are cost savings from material, energy and land filling fees. New market opportunities are also created and revenue from sale of recyclable glass is generated. Due to the new market opportunity, recycling contributes society in creating new employments.

On the other hand, recycling may also result with some drawbacks related to product quality, worker health and safety. One key point of glass recycling is color separation. Since contamination and imbalance in color are two reasons of quality defect, training of waste generators is required to ensure containers are properly separated and inspected before recycling. If glasses of different colors are mixed, this mixture can only be used in the green furnace. Furthermore, noise and human wound are the possible negative results of recycling that effects worker health and safety. Precautions must be taken during the cullet making process. Safety gear such as heavy gloves, long sleeves, boots, and eye protection should be worn to protect handlers from broken and flying glass shards.

4.1.5.2. Reuse. A good way to make packaging more sustainable is to reuse the package in its original form. Multi-way containers are reused when they are returned to collection centers. After collection, they are transported to filling facility for cleaning and re-filling operations described in usage stage.

Reuse option has significant financial and environmental benefits similar to recycling. On the other hand, it has different difficulties and disadvantages. First of all, it requires energy to transport and water to clean used packaging. There are also some other economical difficulties. The initial capital investment of reusable packaging is much higher than for the disposable packaging, and also the reverse logistics of the empty packaging material is another cost element for reusable containers. Technical limits are only related to the quality of reusable packaging. Due to reusing, there may be defects as a result of ineffective control. Furthermore, customer convenience influences the reuse rate based on the choice between one-way and multi-way containers, and by the level of return.

Reuse can be promoted by financial incentives, encouragement and raising awareness among customers. Deposit systems are instruments for organizing economic interests. They give incentives or disincentives for retake and reconditioning of used reusable packaging product. Education for both the producer and the consumer on product take-back and reuse is essential. It helps producers to stay on top of trends, benefit from the experience of others, and identify new opportunities for improving product design and the take-back system from both environmental and business perspectives. Additionally, public education on these issues will improve consumer buying decisions in favor of products that can be returned and reused. This is likely to lead to pressure on producers to design their products for disassembly, remanufacturing and reuse.

4.1.5.3. Landfilling. It is the last option of end of life. The glasses not recycled and not reused are landfilled by the municipalities. Although the raw materials of glass are natural and do not harm the environment too much in landfilling, this option has also some negative aspects.

Since the raw materials are utilized once, sustainability is not achieved when the glass is landfilled. Only raw materials are consumed for the production of new containers in the case of total landfilling, and the resources of the universe are consumed. Additionally, the space requirement for landfilling creates a serious problem. There are not enough spaces for landfilling all of the garbage. Hence, finding different solutions is essential for sustainability.

## **4.2. Life Cycle Inventory Assessment Application**

The application of the life cycle inventory analysis accounts for the raw material consumptions, emission and particle amounts of producing 200,000 kg glass for colorless, amber, and green containers. These data are employed in comparison of technical attributes part of the quality function deployment. The raw material and emission amounts of specified design alternatives in quality function deployment are generated based on these standard data. Technical information is provided from the glass manufacturing facility Şişecam A.Ş., and the data are gathered from an extensive study which is carried out as a

master thesis in Boğaziçi University Institute of Environmental Sciences. The thesis covers full scale Life Cycle Assessment implementation for Şişecam glassware bottles. The data sets are reflected at Table 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7 (Alkan, 2004).

#### 4.2.1. Raw Material Consumptions

Raw materials mentioned in Section 4.1.1 are examined in more detail in life cycle inventory analysis. The color is the primary attribute in obtaining raw material batch. Hence, raw material indices are categorized according to color. Table 4.2 displays the standard batch values for the production of 200,000 kg colorless, amber, and green containers where Table 4.3 shows the data for other resources used in the production process.

Table 4.2. Batch values for producing colorless/amber/green containers.

RAW MATERIALS	COLORLESS		AMBER		GREEN	
	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%
Yalıkoy Sand	77305.506	28.377	-	-	-	-
Safaalamı Sand	61615.449	22.617	-	-	-	-
Yellow Sand	-	-	109381.110	45.467	-	-
Sand	-	-	-	-	78488.860	43.805
Dolomite	22673.491	8.323	8526.450	3.544	15809.460	8.823
Limestone	19693.287	7.229	25142.630	10.451	11580.170	6.463
Soda	34378.516	12.619	32401.490	13.468	21930.410	12.240
Feldspar	152.274	0.056	-	-	8364.210	4.668
Cerium Oxide	37.893	0.014	-	-	-	-
Zinc Selenite	4.487	0.002	-	-	-	-
Sodium Sulfide	1136.951	0.417	203.480	0.085	1270.800	0.709
Chromate	-	-	-	-	749.860	0.419
Cobaltoxide	0.051	0.000	-	-	3.670	0.002
Pyrite	-	-	309.600	0.129	-	-
Perlite	-	-	27543.170	11.449	-	-
Sulphur	-	-	98.900	0.041	-	-
Monobutylinetinrichloride	0.019	0.000	0.019	0.000	13.770	0.008
Cullet produced	55427.800	20.346	36967.000	15.366	40963.800	22.862
Polyethylene wax	0.002	0.000	0.002	0.000	1.720	0.001

Table 4.3. Other resources for producing colorless/amber/green containers.

OTHER RESOURCES	COLORLESS		AMBER		GREEN	
	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%
Coal	71.096	4.943	137.050	9.090	-	-
Natural Gas	3.111	0.216	6.434	0.427	23304.500	94.470
Diesel	1364.200	94.841	1364.200	90.483	1364.200	5.530

#### 4.2.2. Emissions to Air

Glass manufacturing is a very energy intensive activity that results with the emission of combustion by-products such as sulfur dioxide, carbon dioxide, and nitrogen oxides. Melting the furnaces contributes between 80% and 90% of the total pollutant emissions to air from a glass production facility. Emissions occurred in forming and finishing phases are related to the various types of glass production processes. Moreover, container press and blow machines generate huge amounts of emissions due to contact between molten glass and equipment lubricants. Hence, most of the emissions are produced in manufacturing stage.

In the transportation stage, emissions vary because of changing distribution distances. Since the emissions of washing in the usage stage are not considered in the analysis, the usage stage contains only filling operation. Usage emissions are same for all colors, since filling operation does not depend on color. Besides, recycling includes reprocessing activities such as cullet producing emits more than landfilling. Emissions through all life cycle stages are listed at Table 4.4, 4.5 and 4.6 for 200,000 kg batches of each color.

Table 4.4. Emissions of colorless containers.

	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>2</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC (kg)
Manufacturing	19.430	38007.000	4.093	97.378	0.217	6.649
Transportation	5.154	1552.700	1.483	19.140	0.087	2.592
Usage	4.268	1175.000	1.124	11.197	0.087	2.584
Recycling	1.860	341.510	0.329	3.021	0.038	1.280
Landfilling	0.678	124.540	0.120	1.102	0.014	0.411

Table 4.5. Emissions of amber containers.

	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>2</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC (kg)
Manufacturing	18.140	32842.000	4.093	137.110	0.217	6.445
Transportation	4.838	457.400	1.392	17.965	0.082	2.433
Usage	4.268	1175.000	1.124	11.197	0.087	2.584
Recycling	2.940	539.960	0.520	4.770	0.060	1.784
Landfilling	0.678	116.890	0.113	1.034	0.013	0.399

Table 4.6. Emissions of green containers.

	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>2</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC(kg)
Manufacturing	31.610	26008.000	99.763	329.730	0.217	6.449
Transportation	3.282	988.650	0.944	12.187	0.055	1.650
Usage	4.268	1175.000	1.124	11.197	0.087	2.584
Recycling	8.254	1515.900	1.460	13.410	1.168	5.008
Landfilling	0.432	79.298	0.076	0.702	0.009	0.292

#### 4.2.3. Emitted Particulates

Particulates are other significant pollutants which exist in glass manufacturing. All sub-sectors within the glass manufacturing industry contain powdered, granular, or dusty raw materials. Raw materials storage and mixing are two main reasons of particulates.

Similarly, dust emissions are also the result of raw materials transportation, handling, storage, and mixing. Dust generated by these processes is typically coarser than the

particulates emitted from the furnace. Therefore, dust emitted from handling processes is mostly considered as an Occupational Health and Safety (OHS) issue, and particulates which are generated by the hot processes in the batch plant are taken as a potential environmental issue. The particulates in each life cycle stage are presented at Table 4.7.

Table 4.7. Particulates through all life cycle.

	Manufacturing (kg)	Transportation (kg)	Usage (kg)	Recycling (kg)	Landfilling (kg)
Colorless	7.900	0.980	1.041	0.305	0.110
Amber	8.290	0.920	1.041	0.483	0.104
Green	67.160	0.624	1.041	1.355	0.071

### 4.3. Life Cycle Costing Application

Life cycle costing of packaging materials is a recent and popular subject in the context of European Packaging Directive. Since the cost data are kept confidential by the most of the glass manufacturing and recycling companies, real data could not be utilized in this study. Hence, it is obtained from available literature. The two reliable studies are taken as references in life cycle costing of glass beverage containers which are from an international research company and an Israel real case.

Internal costs of a glass container are production cost, transportation cost from glass factory to fillers, filling cost, and transportation cost from fillers to distribution. These cost values are assumed taking into account the transport distance between filler to distributor, recycling rate, and container amount. Table 4.8 indicates the costs of one-way containers for production, distribution, and usage for a specific scenario (RDC and Pira, 2001). Moreover, deposit system has extra cost values compared to single use containers. These extra costs are related to deposit infrastructure, collection, sorting, washing, and other transportation costs between deposit container processes. Table 4.9 displays the costs of multi-way which are reused five times (RDC and Pira, 2001).

Table 4.8. Cost data for one-way containers excluding end of life.

ASSUMPTIONS				
Transport distance from filler to distributor (km)	0	1800	0	1800
Recycling rate (%)	42	42	91	91
Number of containers for filling 1000 lt beverage (kg)	3030.30	3030.30	3030.30	3030.30
Weight of containers required for filling 1000 lt beverage (kg)	666.67	666.67	666.67	666.67
COSTS				
Cost of glass production (€)	132.53	132.53	132.53	132.53
Cost of transport from factory to fillers (€)	10.20	10.20	10.20	10.20
Filing cost (€)	223.43	223.43	223.43	223.43
Cost of transport from fillers to distribution (€)	0.00	2988.00	0.00	2988.00

Table 4.9. Cost data for multi-way containers excluding end of life.

ASSUMPTIONS				
Return rate	100	100	50	50
Transport to market including distance from filling to market and back again (km)	0	3600	0	3600
Number of containers for filling 1000 lt beverage (kg)	606.06	606.06	1212.12	1212.12
Weight of containers required for filling 1000 lt beverage (kg)	200	200	400	400
COSTS				
Cost of glass production (€)	39.76	39.76	79.52	79.52
Cost of transport from glass factory to fillers (€)	3.06	3.06	6.12	6.12
Fillers cost (€/1000l purchased product)	71.58	71.58	71.58	71.58
Cost of transport from fillers to distribution (€)	0.00	2988.00	0.00	2988.00
Cost of deposit infrastructure (€)	27.62	27.62	55.24	55.24
Cost of transport from deposit to sorting plant (€)	4.01	4.01	2.005	2.00
Cost of sorting before washing (€)	11.70	11.70	5.85	5.85
Cost of transport from sorting to fillers (€)	0.00	2988	0.00	1494.00
Cost of washing (€)	75.15	75.15	37.57	37.57

End of life costs, which are recycling and landfilling, costs are same for one-way and multi-way containers. However, the collection of containers differs in these two types. One-way containers are brought to collection points by customers and collected by municipalities whereas multi-way containers are collected by beverage filling facilities.

Table 4.10 presents the costs of all end of life options (RDC and Pira, 2003 and Lavee, 2010).

Moreover, there is a cost to society occurs due to emissions. Unfortunately, it is very hard to calculate the emissions' costs to society, and another way to show these costs the environmental tax concept is acceptable. One of the most famous environmental taxes is called eco-tax which is applied in Netherlands for packaging materials. This tax is 71.8 € per tonne, and it is used as the cost of emissions' damages in this study (Nedvang, 2010).

Table 4.10. Cost of end of life.

COLLECTION COSTS FOR MULTI-WAY CONTAINERS	
Retailer cost (€/container)	0.013858
Cost of collection stations (€/container)	0.009898
Cost of automatic collection machine (€/container)	0.003959
Cost of collectors (€/container)	0.008909
COLLECTION COSTS OF ONE-WAY CONTAINERS	
Municipality collection cost (€/tonne)	22.56853
LANDFILLING COSTS	
Landfill cost (€/tonne)	19.79695
Landfill tax cost (€/tonne)	9.898477
COSTS OF RECYCLING	
Cost of cullet preparation (€/tonne)	20.600000

#### 4.4. Quality Function Deployment Application

The product design alternatives are generated and assessed in the second phase of proposed methodology. Quality function deployment is employed for translating customer requirements to technical specifications. Customer term is categorized into segments, and their requirements are defined, accordingly. Technical attributes of the product are detailed and analyzed. At the last part of the QFD, comparison of technical attributes and customer satisfaction are applied.

#### **4.4.1. Defining Customer**

Sustainable packaging is considered as the packaging design with the lowest environmental impact that provides the required functionality. From this point of view, customer is not only the end user demanding quality requirements, instead customer is defined as a group consists of end user, employees, and society expressing their requirements from the product. Thus, the stakeholders of the system are society, workers of manufacturing and recycling, transporters, and customers buying the product. All of these stakeholders are modified for sustainability concept and divided into groups:

- External customer: Beverage companies and end users.
- Internal customer: Workers of manufacturing, recycling and transportation.
- Society: All other people.

#### **4.4.2. Defining Customer Needs**

In this part of the study, the customer needs and expectations are listed according to life cycle stages and customer segmentation. External customer, internal customer, and society are introduced, and their requirements from the glass beverage container are specified respectively in Table 4.11.

External customer consists of beverage companies and people who buys beverage packaged with glass container. Although glass container is the end product of glass manufacturing facility, it is actually a co-product used as packaging material in beverage companies. Beverage companies are in the first customer group buying the product whereas consumers are in the second one as buying it filled with beverage. In these two groups, the critical customer type refers to consumers, because beverage companies consider consumers' requirements in choosing their products' bottle design. For this reason, in this study, consumers are taken into account and asked for requirements.

Requirements are matched with the general requirement framework mentioned in Section 3.2. The safety issue in raw materials is expressed as minimum adverse health/safety impacts. The primary needs are mostly in the usage stage of the life cycle are mentioned as Garvin's quality characteristics. Deliverability in the distribution stage is defined as near sale and recycling points. Additionally, reversibility requirement in the end of life stage is detailed as ease of sort, recycling, reuse, and disposal. Some of the requirements of external customer are detailed below:

- Near sale and recycle points: This expectation refers to accessing the product easily from the distribution points, and getting service about end of life options after the product is used. Service at the end of life can be in the form of collection of glass from houses, or available glass recycling containers in the neighborhoods of customers, or other collection points for reusing the containers.
- Lightness: The glass is the heaviest packaging material for beverages, and in order to get an advantage against to other packaging materials decreasing weight of the container should be taken into account. Therefore, it is quite essential.
- Cheapness: The cheapness of container affects both beverage companies and consumers. Apparently cost of beverage filled container decreases, if the container is cheap.
- Durability: The length of product's life can be defined by durability attribute. The container should not be broken or harmed easily at filling and transportation processes.
- Aesthetics: Aesthetics is the product's way of affecting individual's five senses. The customer is faced with aesthetics in the usage stage.
- Light reflection - protection of beverage: Light can pass though the glass containers, and the beverage can be spoil. However, it can be prevented with adjusted glass properties.
- Easy to use - handle and drink: The containers are needed to be handled easily and used.

Sustainability concept also considers employees and takes into account their needs. These needs are mostly related to health and safety problems that can occur in the manufacturing and recycling stages. The significant occupational health and safety hazards take place in the operational phase of glass manufacturing, and primarily they are the

results of exposure to heat, noise, respiratory, physical, and electrical hazards. For avoiding these problems in raw materials and manufacturing stages, and making the work of employees easier, manufacturing workers' needs are listed as in Section 3.2. Moreover, the expectations of recycling workers are intensified in end of life. Sorting the waste of glass is the major problem for them, since it wounds their parts of body. This problem also supports the other health, safety and easiness requirements, and it can be solved with modifying the recycling and reuse system.

The sustainability of packaging is improved by society requirements based on design for environment strategies and governmental regulations. Main principle in environmental strategies can be defined as reduce, reuse and recycle as much as possible. Dematerialization is the requirement of society associated with reduction. One simple way to corroborate the sustainability of packaging is to use less of it, which can be achieved by reducing size, thickness, and weight. Over the last 30 years, the packaging industry has made great strides in reducing the weights. Glass containers are around a third lighter than in 1980. Reduction of packaging cuts down on the consumption of materials, and it also requires less energy to manufacture and transport. As well as being less detrimental for the environment, reduced costs provide a strong incentive for companies to minimize packaging.

Recycling and reusing are promoted by the society, and always preferred against to landfilling end of life option. In this viewpoint, design for recycling and design for reuse are other two concepts that are supported. When the processes are lean and simple, less environmental impact and costs occur. Thus, leanness of processes in the product system is also demanded by the society.

Table 4.11. Voice of customer.

		<i>External Cust.</i>	<i>Internal Cust.</i>	<i>Society</i>
	<b>Customer Requirements</b>			
<i>Raw materials</i>	Minimum adverse health/safety impacts	x	x	x
	Less resource usage /Dematerialization			x
	Ease of recovery, reuse, recycling			x
	Ease of extraction and processing			x
	Ease of transportation from supplier			x
<i>Production</i>	Working conditions at company; health & safety		x	
	Clean processes and production technology		x	x
	Less emissions to air		x	x
	Minimum waste and effluents		x	x
	Minimum energy usage			x
	More local investments		x	x
	Positive impacts on local community			x
<i>Distribution</i>	Near sale and recycle points	x		
	Easy to package		x	
	Less packaging material		x	x
	Less emissions to air			x
	Less waste			x
<i>Usage</i>	Lightness	x		
	Cheapness	x		
	Durability	x		
	Aesthetics	x		
	Light reflection - protection of beverage	x		
	Easy to use - (handle and drink)	x		
	Proper usage style of the product			x
<i>End of Life</i>	Conformance to standards	x	x	x
	Easy to sort	x	x	
	Ease of recycling, reuse, disposal	x	x	x
	Minimum adverse health/safety impacts of end of life options		x	x
	More recycling and reuse rather than disposal			x

#### **4.4.3. Defining Technical Attributes**

The engineering characteristics that are critical to develop the product in order to meet customer requirements are listed in this section. The main attributes of the beverage container are the physical characteristics that can be observed such as volume, weight, height, diameter, shape, color, and thickness. Additionally, the color and weight attributes are strongly correlated with raw material index and amounts. Hence, specifying them is significant for environmental assessment.

In addition to raw material index and amounts, environmental point of view takes the pollutants and toxic material amounts into consideration as technical specifications. Moreover, all life cycle system is taken into account in technical attributes. Hence, not only the product attributes, but system attributes such as recyclability/landfilling ratio, deposit system, traceability, distribution channel, sign/instructions are also considered in sustainable design.

#### **4.4.4. Constructing Relationship Matrix**

Relationship matrix combines customer requirements and technical specifications of the product by defining a relationship between them. Roughly, it is constructed with following general principles gathered from glass production facility. Requirements of raw materials life cycle stage have connection with material's attributes and color, since color choice affects the material index directly where external customer's requirements from the usage stage are strictly related to product's physical attributes. Lastly, other environmental requirements stated in various life cycle stages are mostly matched with pollutants, raw materials and system attributes such as deposit system, recyclability ratio and distribution channel.



#### 4.4.5. Correlation Matrix

Correlation matrix of HOQ identifies relationships among technical requirements. Raw material index directly varies in accordance with the color choice. Any change in the index and raw material amount affects mass of pollutants. Mass of pollutants is also affected from the other factors that are correlated with raw material amounts such as volume, weight, and thickness. Toxicity of materials is strictly in a relationship with the material type that is to be used, raw material index, and color which specifies raw material index. As the recycling ratio and selected deposit system is increased, mass of pollutants decreases.

Additionally, diameter change affects volume when height is fixed. On the other hand, if the volume is constant for containers, decreasing the diameter increases height value. However, shape option is not correlated with any other technical attribute. These options are selected from the mostly used standard containers in the facility. In accordance with shape and other physical attributes, molds are prepared in the facility, and containers are produced by these molds. Height and diameter are specified in agreement with volume and shape. Moreover, different volume options may have same shapes with various height and diameter values like same volume options with different shapes.

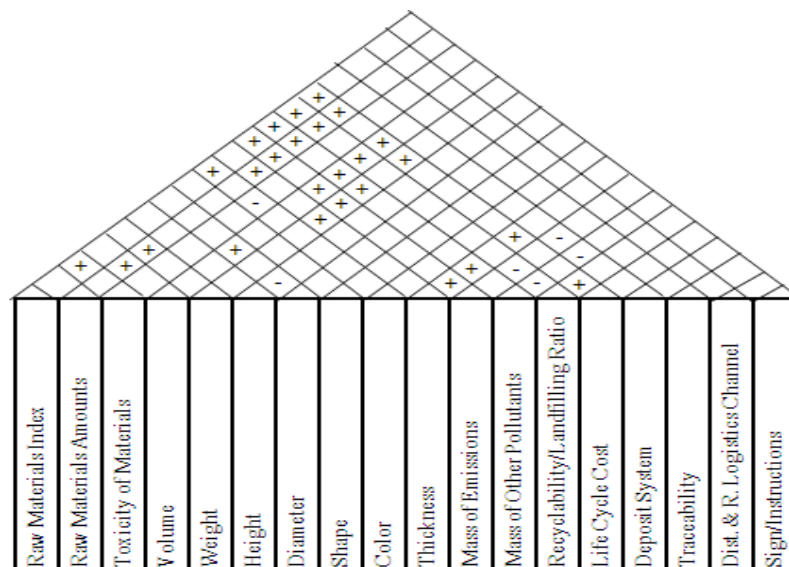


Figure 4.3. Roof part of HOQ.

#### 4.4.6. Comparison of Design Alternatives

Comparison is one of the most vital parts of the House of Quality. It enables examine the design alternatives which are also called as scenarios. The comparisons are performed with considering the technical specifications and requirement satisfaction levels of scenarios that are generated according to most crucial technical attributes in the House of Quality. In the following, generation of design alternatives is presented, and then comparison studies are illustrated.

#### 4.4.7. Scenario Analysis

In order to analyze possible glass beverage container design alternatives, scenarios are generated considering the most important technical attributes: color, volume, recycle ratio and deposit system. Other technical attributes generally depend on these important ones. Hence, they are not taken as parameters in these scenarios. The compatibility of various design elements is displayed in Table 4.13. Value of 1 indicates that these two design elements are compatible and can be included in any single design alternative, whereas N/A sign indicates that the elements are incompatible and they cannot be in the same design alternative.

Table 4.13. Compatibility matrix of various design elements.

Color	Colorless									
	Amber	N/A								
	Green	N/A	N/A							
Volume	330	1	1	1						
	500	1	1	1	N/A					
Recycle Ratio	30	1	1	1	1	1				
	60	1	1	1	1	1	N/A			
	90	1	1	1	1	1	N/A	N/A		
Deposit	Yes	1	1	1	1	1	N/A	N/A	1	
	No	1	1	1	1	1	1	1	1	N/A
	Colorless	Amber	Green	330	500	30	60	90	Yes	No
	Color			Volume		Recycle Ratio			Deposit	

According to this matrix, design alternatives include one option of each design element. There are three options for color: colorless, amber, and green. Two alternatives of volume are adopted which are 330 ml and 500 ml. Recycle ratios are assumed as 30%, 60% and 90% for one-way containers. 30% is the lowest target which is also very close to the target of Turkey, whereas 60% is the general recycling rate accepted by the European Union. The legislations related to glass packaging material waste state that 38% recycling ratio is compulsory in Turkey, and 60% in European countries. Moreover, 90% is a very high recycling ratio that expresses the perfect case of recycling, and it is the indicator of almost perfectly working recycling system.

Table 4.14. Scenarios - design alternatives.

Scenario No.	Color	Volume (ml)	Deposit System	Recycling Ratio (%)
1	Colorless	330	Yes	90
2	Amber	330	Yes	90
3	Green	330	Yes	90
4	Colorless	330	No	30
5	Colorless	330	No	60
6	Colorless	330	No	90
7	Amber	330	No	30
8	Amber	330	No	60
9	Amber	330	No	90
10	Green	330	No	30
11	Green	330	No	60
12	Green	330	No	90
13	Colorless	500	Yes	90
14	Amber	500	Yes	90
15	Green	500	Yes	90
16	Colorless	500	No	30
17	Colorless	500	No	60
18	Colorless	500	No	90
19	Amber	500	No	30
20	Amber	500	No	60
21	Amber	500	No	90
22	Green	500	No	30
23	Green	500	No	60
24	Green	500	No	90

For the multi-way containers, recycling rate equals to return rate. Since these containers return to beverage filling facility, at the end of their life they are recycled with the return rate. All of the returned containers are sent to recycling, and in average this return rate is 90%.

#### **4.4.8. Comparison of Technical Attributes**

Technical comparison of scenarios is accomplished with considering the technical attributes of design alternatives. Raw materials index consumption amounts, their toxicity status, and mass of emissions of design alternatives are compared in parallel to life cycle analysis application in Section 4.2. Physical attributes such as color, volume, weight, height, diameter, thickness, and shape are displayed in accordance with the real life containers. Life cycle costs of design alternatives are calculated with life cycle costing application which is mentioned before in Section 4.3. Moreover, system attributes are grouped as deposit system, recyclability/landfilling ratio, traceability, distribution channel/reverse logistics, and sign/instructions are described separately for design alternatives.

4.4.8.1. Raw Materials Index and Consumption Amounts. Raw materials index refers to the elements used in manufacturing stage of the containers and consumption amounts are the amounts required for production of specific amount of containers. The index is strictly dependent on the color choice and the consumption amounts that are determined in accordance with the amount of containers and unit bottle weight. Batch is the mixture of raw materials with specific amounts including raw material indices and consumption amounts. The standard batch values required to produce 200,000 kg containers are presented for colorless, amber, and green containers in life cycle inventory analysis application in Section 4.2.1.

In this section, standard values are used for generating the raw material consumption amounts of design alternatives. Batch values of scenarios are calculated with linear interpolation. As performed in the standard data, producing 1,000,000 containers case is assumed for all scenarios. Since there is a variety in the container weights and recycling

rates, total batch weights are different for each other. Based on this property, every scenario has different combinations of raw material amounts.

Total weight of each scenario is the multiplication of unit container weight presented in Table 4.16 with the container amount 1,000,000. The ratio between the total weight of each scenario and the total weight of standard data, which is 200,000 kg, equals to the ratio between the raw material amounts of scenarios and raw material amounts of standard data. Hence, the raw material amounts of one-way scenarios are calculated in this way. On the other hand, for multi-way scenarios, in order to find the raw material amount per usage, the calculated raw material amounts are also divided to trippage rate.

As a subsequent process of calculation of raw material amounts, the effect of recycling rate is also taken into account. Since the increasing recycling rate decreases raw material consumption for each scenario, the reduction amounts are calculated to illustrate the raw material consumption amounts. The reductions in the raw materials as the result of increasing recycling rate are obtained from Glass Packaging Institute (2010). Every 10 % increase in recycled glass equals to:

- 10 % decrease in sulfur dioxide (SO<sub>2</sub>),
- 6 % decrease in nitrogen oxide (NO<sub>x</sub>),
- 17 % reduction in carbon dioxide (CO<sub>2</sub>),
- 2.5 % reduction in electricity and natural gas,
- Six degree Celsius reduction in furnace temperature,
- 9.5 % reduction in raw materials.

Table 4.15. Raw material consumption amounts of scenarios.

Scenario No.	Raw materials (kg)	Cullet (kg)	Batch (kg)
1	50240.355	27327.315	77567.669
2	66662.224	24817.169	91479.392
3	37462.775	14897.815	52360.590
4	179094.105	113311.418	292405.523
5	133001.551	243143.204	376144.755
6	98818.371	446509.120	545327.492
7	262813.624	87302.534	350116.158
8	195205.288	216677.978	411883.266
9	145063.308	422135.013	567198.320
10	178525.183	88835.171	267360.354
11	138558.086	211877.290	350435.376
12	107514.226	352170.727	459684.954
13	81913.622	44555.404	126469.026
14	87173.677	32453.220	119626.898
15	58148.742	23123.999	81272.741
16	322369.388	148468.016	470837.405
17	239402.791	289936.637	529339.428
18	177873.068	508791.179	686664.247
19	324136.803	153834.121	477970.924
20	240753.189	305231.520	545984.709
21	178911.413	539999.777	718911.190
22	321345.329	117503.277	438848.606
23	249404.554	254702.485	504107.039
24	193525.607	403989.213	597514.821

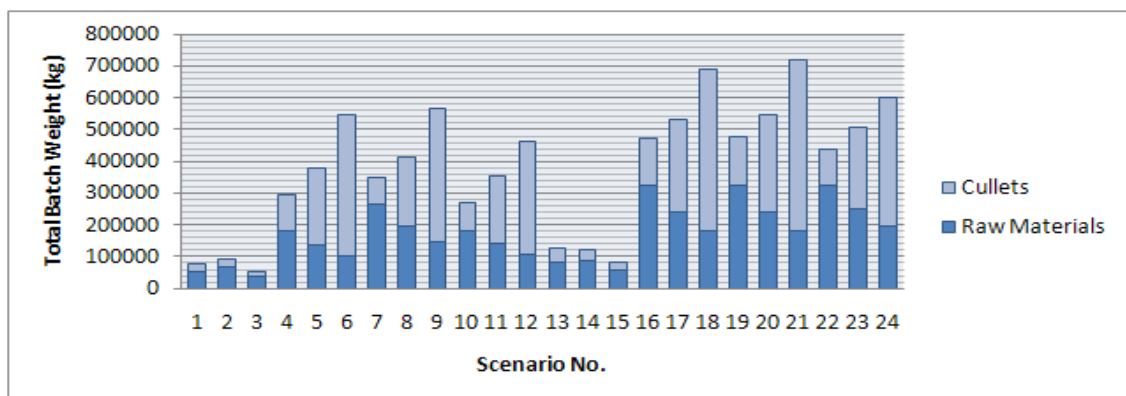


Figure 4.4. Raw material and cullet usage amounts of scenarios.

As in the calculated results illustrated in Figure 4.4 and Table 4.15, the raw material consumption amounts of scenarios with 500 ml are more than scenarios with 330 ml volume option. As recycling rate increases, cullet amounts increase and raw material consumption decreases. Since multi-way containers are used five times, their raw material consumption amounts are less than one-way containers. Even the scenarios with 500 ml and deposit system have less batch weight than one-way containers.

4.4.8.2. Toxicity of Materials. In the literature, toxicity assessment of glass is performed by Pira and Econas (2005). In accordance with this study, mercury (Hg) and cadmium (Cd) are detected in very low levels with sophisticated detection methods. On the other hand, another toxic material, chromium (Cr) is raw material of green glass. In order to obtain green color, chromium is included in the inventory of green glass container with high levels.

The last toxic material examined in the same study is lead (Pb), which is also concluded as a significant toxicity factor due to recycling processes of the glass. It is concluded that lead comes out from separable and non-separable impurities of the cullet in this life cycle stage and can also be reduced with techniques that eliminate separable impurities such as ceramics, porcelain, and stones.

4.4.8.3. Color – Volume – Weight. Three color alternatives are considered in the scenarios. They are selected as the mostly sold glass beverage containers which are colorless, amber, and green. Colors in scenarios are defined as:

Colorless = {1, 4, 5, 6, 13, 16, 17, 18}

Amber = {2, 7, 8, 9, 14, 19, 20, 21}

Green = {3, 10, 11, 12, 15, 22, 23, 24}

Additionally, two different volume options are identified for satisfying customer requirements which are the options most preferred by the customer. The two options are separated equally in scenarios. The first twelve scenarios have volume 330 ml, and the rest of the scenarios have volume 500 ml.

Since the product life cycle assessment is performed in consideration of weights, the weight is an essential benchmarking attribute. The glass containers with higher weights consume more raw materials and produce more emissions than the containers having lower weights. Moreover, weight is necessary for assessing the lightness of container which is stated as a customer requirement. Hence, container is required to be as light as possible. Unit glass container weights of scenarios are shown in Table 4.16.

Table 4.16. Unit glass container weights in scenarios.

Scenario No.	Weight (kg)	Scenario No.	Weight (kg)
1	0.230	13	0.375
2	0.325	14	0.425
3	0.230	15	0.375
4	0.200	16	0.360
5	0.200	17	0.360
6	0.200	18	0.360
7	0.300	19	0.370
8	0.300	20	0.370
9	0.300	21	0.370
10	0.200	22	0.360
11	0.200	23	0.360
12	0.200	24	0.360

4.4.8.4. Height – Diameter – Thickness – Shape. The measurements of glass containers are based on specific designs which already exist in the product catalogue of the manufacturing company. These designs could be very various ways. New measures and shapes can also be designed after the request of the beverage company.

In the physical attributes of the glass containers, one crucial point is related with the thickness. Multi-way containers are produced thicker than one-way containers, since they are used for many times. Hence, in order to ensure durability of the container, optimal thickness is needed to be ensured. The measures of various glass container designs are displayed in Appendix A at Table A.1.

4.4.8.5. The Mass of Emissions and Other Pollutants. In accordance with the life cycle inventory assessment application, emissions of scenarios in all over the life cycle stages are generated, similar to the calculation of raw material amounts. The mass of air pollutants occurs in various life cycle stages of product which are manufacturing, usage, recycling and landfilling. In this section, the total emission amounts are listed, and emissions at life cycle stages are described shortly.

The manufacturing emissions per usage in multi-way scenarios are fewer than one-way scenarios due to reusing the same container more than once. Since increasing recycling rates rise cullet usage, and cullet melts in the furnace in lower temperatures, there exists less manufacturing emissions in high recycling rates. In color comparison, amber color produces the highest emissions in multi-way scenarios whereas colorless option has the highest emission values in one-way alternatives. In each scenario, green option has the least emission amounts. Additionally, volume is a critical criterion for emission amounts. If volume increases, weight of the container increases directly, and this results with more emissions. Hence, scenarios with volume option 500 ml have more emission amounts than 330 ml cases.

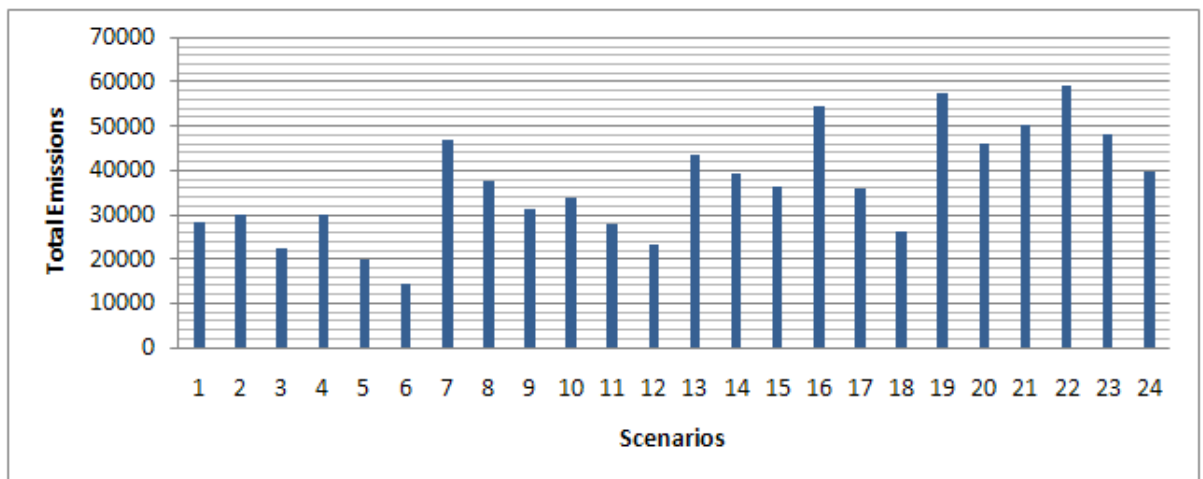


Figure 4.5. Comparison of total emissions in scenarios.

Table 4.17. Total emission amounts of scenarios.

Scenario No.	Manufact. (kg)	Transport. (kg)	Usage (kg)	Recycl. (kg)	Landfil. (kg)	Total
1	8772.813	9097.282	6872.981	3605.350	16.225	28366.256
2	10730.296	3940.869	9711.821	5750.937	15.944	30151.775
3	6104.874	5792.504	6872.981	3811.153	16.037	22598.380
4	26300.388	1582.136	1195.301	1045.029	98.758	30227.329
5	15065.754	1582.136	1195.301	2090.058	56.433	19993.920
6	8636.795	1582.136	1195.301	3135.087	14.108	14566.568
7	42275.704	727.545	1792.952	1769.519	145.573	46718.815
8	31352.089	727.545	1792.952	3539.038	83.184	37500.383
9	23251.983	727.545	1792.952	5308.557	20.796	31105.965
10	29394.810	1511.088	1792.952	1104.682	146.421	33953.959
11	22188.285	1511.088	1792.952	2209.364	83.669	27788.383
12	16490.954	1511.088	1792.952	3314.046	20.917	23132.199
13	14303.500	14832.525	11205.947	3265.716	26.453	43636.758
14	14031.925	5153.444	12700.073	7520.455	29.461	39437.856
15	9475.826	9444.300	11205.947	6213.837	26.147	36367.347
16	47340.699	2847.845	2151.542	1881.052	152.370	54383.798
17	27118.358	2847.845	2151.542	3762.104	76.185	35963.661
18	15546.231	2847.845	2151.542	5643.157	25.395	26219.823
19	52140.035	897.306	2211.307	2182.407	179.540	57619.871
20	38667.576	897.306	2211.307	4364.813	102.594	46250.472
21	28678.093	897.306	2211.307	18392.958	25.649	50210.408
22	52910.658	1813.306	2151.542	1988.428	175.705	59046.851
23	39938.914	1813.306	2151.542	3976.856	100.403	47986.464
24	29683.717	1813.306	2151.542	5965.284	25.101	39642.984

In the transportation stage, the emissions of multi-way scenarios are much more than one-way scenarios. The reason is the travel distance in reverse logistics of empty containers and distribution of refilled containers. The same container is used five times, and transportation emissions are five times higher than one-way scenarios. On the other hand, it is assumed that in one-way scenarios transportation distance does not depend on recycling rate. In all one-way scenarios, transportation emissions are the same.

Similar to transportation stage, in the usage stage multi-way scenarios have more emission amounts than others due to the same reason. Since containers in one-way scenarios are filled one time, they have almost the same emission amounts. At the end of

life options, recycling produce emissions more than landfilling. As recycling rate increases, recycling emissions increase and landfilling emissions decrease.

The emission amounts of scenarios at separate life cycle stages are indicated in Appendix B at Table B.1, B.2, B.3, B.4 and B.5, and the total emission amounts are presented in Table 4.17. The scenario with the highest emission amounts is Scenario 16. Minimum emission amounts are obtained in Scenario 6, 11 and 12. Moreover, soil and water pollutants are included in the other pollutants category. The information of water pollutants is not available. Hence, the mass pollutants of scenarios are considered and presented in Table B.6.

4.4.8.6. Deposit System and Reverse Logistics. Glass beverage containers are one-way or multi-way as described in usage life cycle stage in Section 4.1.4. Scenario 1, 2, 3, 13, 14, and 15 are generated for multi-way whereas the others are one-way. The processes of one-way and multi-way containers are same with described in Section 4.1.4. Additionally, a flow chart is displayed for illustration of the systems in Appendix C.

One-way containers are used one time, and then recycled or landfilled. In recycling process, stakeholders are municipality, collection center and cullet facility. Following to recycling, cullet are transported to manufacturing facility Şişecam A.Ş. for mixing with other raw materials.

On the other hand, multi-way containers are returned to filling facility and reused. The containers returned to sales points are transferred to the filling facility to be cleaned and filled again. If the customer does not bring the glass beverage container back, it is thrown to garbage. Additionally, filling facility controls the returned containers. If any defect is found that may decrease the quality of the container, these are dispatched to recycling facilities at once. Moreover, reverse logistics systems of one-way and two-way containers are different from each other. One-way containers are picked from recycling containers, and two-way containers are accumulated in sale points.

4.4.8.7. Recyclability and Landfilling. Recycling ratio of one-way containers is dependent on the customer in one-way scenarios. Participation in recycling schemes involves developing waste awareness campaigns and new usage habits.

Contrary, recycling is not the problem for two-way containers. The problem is whether the container is going to return to the filling facility or not. Fortunately, customers of two-way containers are much aware of the environmental footprint of containers, and 90 % of customers bring the containers back. The containers are transported to recycling by the filling facility. Therefore, all of the returned containers enter to recycling.

As a result, the diversity in recycling ratios of scenarios is enabled. Scenarios with multi-way bottle have 90 % recyclability whereas scenarios with one-way containers have recyclability ratios 30 %, 60 %, and 90 %.

4.4.8.8. The Additional Attributes. The additional attributes for glass beverage containers suggested in this thesis are traceability and sign/instructions. In real life, traceability of the product is not available through life cycle stages. Therefore, obtaining the certain recycling and reusing rates are rather tough. Traceability is a new suggested attribute that enables to track containers whether they are used again, or not brought back for two-way containers, and whether they are junked, or brought to recycling containers. This attribute is considered in all of the scenarios.

Extra sign for promoting recycling in one-way containers and for bringing back in two-way containers are also regarded as necessary, and recommended. Thus, labels provide a direction to consumers in usage and recycling. Moreover, package development involves considerations for sustainability, environmental responsibility, and applicable environmental and recycling regulations.

4.4.8.9. The Life Cycle Costs. Life cycle costs of scenarios are simulated from the life cycle costing analysis of the product explained at Section 4.3, and the cost values in the currency of Euro (€) are listed at Table 4.18.

The cost elements occur in one-way scenarios are glass production cost, transportation costs for from glass factory to fillers, and from fillers to distribution center, beverage filling cost, municipality collection cost, landfilling cost and tax, cullet preparation cost, and eco-tax. From these cost elements, most of them are common for multi-way containers except municipality collection cost, since glass containers are collected back by the beverage filling facility. In addition, there exist other costs related with the re-usage of the containers. Construction of deposit system is the main cost element. Furthermore, cost of transportation from collection points to sorting facility, cost of sorting, washing cost, retailer and collection stations' cost for storage of the containers are the rest of the cost components.

Glass production cost depends on the weight of the scenario. For multi-way alternatives production cost is divided to trippage rate to illustrate the cost for unit utilization. Since cost per usage is calculated, glass manufacturing costs are less in multi-way scenarios. On the other hand, the total transportation costs are higher in multi-way scenarios compared with one-way scenarios. For, all scenarios the cost of transportation processes are also in a relationship with the weight of the containers. The reason of the difference in one-way and multi-way transportation costs is the extra processes occur in collecting the empty containers.

Landfilling operation is less in multi-way scenarios, so the cost of landfilling and its tax is lower in multi-way scenarios compared with one-way scenarios. Cullet preparation cost is correlated with the recycling ratio, and varies in accordance with this factor. Finally, eco-tax is another element varying with the weight of the scenarios.

Table 4.18. Life cycle costs of scenarios.

Sc. No.	Glass prod. (€)	Transport from factory to fillers (€)	Filling (€)	Transport from fillers to distr. (€)	Deposit infrastr. (€)	Transport to sorting (€)	Sorting (€)	Washing (€)	Retail. (€)	Coll. Statio. (€)	Municip. Collect. (€)	Landfil. (€)	Landfill tax (€)	Cullet Prepa. (€)	Ecotax (€)	TOTAL
1	9144.5	703.8	77083.0	257713.7	31763.0	4611.5	13455.0	86422.5	13858.0	9898.0	-	91.1	45.5	852.8	16514.0	522156.4
2	12921.6	994.5	108921.6	364160.7	44882.5	6516.3	19012.5	122118.8	13858.0	9898.0	-	128.7	64.3	1205.1	23335.0	728017.5
3	9144.5	703.8	77083.0	257713.7	31763.0	4611.5	13455.0	86422.5	13858.0	9898.0	-	91.1	45.5	852.8	16514.0	522156.4
4	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	2771.6	1385.8	1236.0	14360.0	358213.4
5	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	1583.8	791.9	2472.0	14360.0	357667.7
6	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	395.9	198.0	3708.0	14360.0	357121.9
7	59638.2	4590.0	100543.0	336148.3	-	-	-	-	-	-	6770.6	4157.4	2078.7	1854.0	21540.0	537320.1
8	59638.2	4590.0	100543.0	336148.3	-	-	-	-	-	-	6770.6	2375.6	1187.8	3708.0	21540.0	536501.5
9	59638.2	4590.0	100543.0	336148.3	-	-	-	-	-	-	6770.6	593.9	297.0	5562.0	21540.0	535682.9
10	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	2771.6	1385.8	1236.0	14360.0	358213.4
11	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	1583.8	791.9	2472.0	14360.0	357667.7
12	39758.8	3060.0	67028.7	224098.9	-	-	-	-	-	-	4513.7	395.9	198.0	3708.0	14360.0	357121.9
13	14909.6	1147.5	125678.7	420185.4	51787.5	7518.8	21937.5	140906.3	13858.0	9898.0	-	148.5	74.2	1390.5	26925.0	836365.4
14	16897.5	1300.5	142435.9	476210.1	58692.5	8521.3	24862.5	159693.8	13858.0	9898.0	-	168.3	84.1	1575.9	30515.0	944713.3
15	14909.6	1147.5	125678.7	420185.4	51787.5	7518.8	21937.5	140906.3	13858.0	9898.0	-	148.5	74.2	1390.5	26925.0	836365.4
16	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	4988.8	2494.4	2224.8	25848.0	644784.1
17	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	2850.8	1425.4	4449.6	25848.0	643801.8
18	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	712.7	356.3	6674.4	25848.0	642819.5
19	73553.8	5661.0	124003.0	414582.9	-	-	-	-	-	-	8350.4	5127.4	2563.7	2286.6	26566.0	662694.8
20	73553.8	5661.0	124003.0	414582.9	-	-	-	-	-	-	8350.4	2929.9	1465.0	4573.2	26566.0	661685.2
21	73553.8	5661.0	124003.0	414582.9	-	-	-	-	-	-	8350.4	732.5	366.2	6859.8	26566.0	660675.6
22	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	4988.8	2494.4	2224.8	25848.0	644784.1
23	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	2850.8	1425.4	4449.6	25848.0	643801.8
24	71565.8	5508.0	120651.6	403378.0	-	-	-	-	-	-	8124.7	712.7	356.3	6674.4	25848.0	642819.5

#### 4.4.9. Comparison of Customer Satisfaction

This section is the part of comparing customer perceptions and satisfaction levels of scenarios. In traditional quality function deployment methodology, it is analyzed in the planning matrix of house of quality with other factors such as improvement factor and sales point. In this study, only customer perceptions are taken into consideration. Satisfaction levels are identified for each requirement and for each design element of scenarios.

A matrix comparing the fulfillment of requirements from elements of design options is constructed for examining customer satisfaction regarding with different design alternatives. All customer requirements listed in HOQ are reconsidered again and questioned to find how much they are satisfied from selected design element. The importance weights of customer satisfaction types are determined according to the interviews with the people who have extend knowledge about the system. The views of the experts in glass manufacturing company Şişecam A.Ş., non-governmental organization Environmental Protection and Packaging Waste Utilization Association (ÇEVKO), and Kadıköy Municipality guide the weight specifications. Therefore, customer satisfaction levels are obtained by other technical comparison results and expert interviews. They are illustrated in Table 4.19. In the matrix, satisfaction levels are accepted as the following.

- 9 – Best satisfying option
- 6 – Medium satisfying option
- 3 – Worst satisfying option
- 0 – No relationship between option and requirement

Table 4.19. Customer satisfaction comparison matrix.

	External Cust. Importance	Internal Cust. Importance	Society Importance	Color			Vol. (ml)		Recycle Ratio (%)			Deposit	
				Colorless	Amber	Green	330	500	30	60	90	Yes	No
Minimum adverse health/safety impacts	6	8	10	9	6	3	9	6	3	6	9	0	0
Less resource usage /Dematerialization	0	0	8.8	9	3	6	9	6	3	6	9	9	6
Ease of recovery, reuse, recycling	0	0	7.4	0	0	0	0	0	0	0	0	9	6
Ease of extraction and processing	0	0	5.4	9	9	9	0	0	0	0	0	0	0
Ease of transportation from supplier	0	0	5.4	9	6	9	0	0	0	0	0	0	0
Working conditions; health & safety issues	0	9	0	0	0	0	0	0	9	6	3	9	3
Clean processes and production technology	0	8.6	8	0	0	0	0	0	3	6	9	9	6
Less emissions to air	0	6	9	9	6	3	9	6	3	6	9	9	6
Minimum waste and effluents	0	5.4	8.8	9	6	3	9	6	3	6	9	9	6
Minimum energy usage	0	0	8.4	9	6	3	9	6	3	6	9	9	6
More local investments	0	7.2	8.6	0	0	0	0	0	3	6	9	0	0
Positive impacts on local community	0	0	7.4	0	0	0	0	0	3	6	9	9	6
Near sale and recycle points	8.4	0	0	0	0	0	0	0	3	6	9	0	0
Easy to package	0	8	0	0	0	0	9	6	0	0	0	0	0
Less packaging, volume, weight	0	8.4	7.4	9	6	6	9	6	0	0	0	0	0
Less emissions to air	0	0	8.4	9	3	6	9	6	0	0	0	9	6
Less waste	0	0	9	0	0	0	9	6	0	0	0	9	6
Lightness	9.4	0	0	0	0	0	9	6	0	0	0	3	9
Cheapness	8.4	0	0	9	9	9	9	6	9	6	3	3	9
Durability	8.4	0	0	0	0	0	0	0	0	0	0	9	6
Aesthetics	6	0	0	0	0	0	0	0	0	0	0	0	0
Light reflection - protection of beverage	6.6	0	0	3	9	9	0	0	0	0	0	0	0
Easy to use - (handle and drink)	6.8	0	0	0	0	0	0	0	0	0	0	0	0
Proper usage style of the product	0	0	6.4	0	0	0	0	0	0	0	0	9	9
Conformance to standards	6.4	7.2	10	0	0	0	0	0	3	6	9	9	9
Easy to sort	7.4	8.6	0	0	0	0	0	0	0	0	0	9	3
Ease of recycling, reuse, disposal	8	8.4	10	3	6	9	0	0	0	0	0	9	6
Minimum adverse health/safety impacts	0	8.4	10	0	0	0	0	0	3	6	9	9	3
More recycling and reuse	0	0	10	0	0	0	0	0	3	6	9	9	3

For instance, first requirement of raw materials stated as “Minimum adverse health/safety impacts” is satisfied mostly in colorless, 330 ml, and 90 % recycle ratio options. The reasons supporting this observation can be listed as the following:

- Raw materials of colorless container have less adverse health and safety impacts.
- As volume decreases, raw materials usage decrease, and less adverse health and safety impacts are obtained.
- Due to the increasing recycling ratio, fewer raw materials are used and less impact occur.

The calculations for scenarios are done by multiplying customer importance with satisfaction level of customer requirement for each option. The weighted satisfactions are obtained as a result of this calculation. The satisfaction levels for all requirements are then summed up to get the total satisfaction level of the scenario. An example of customer satisfaction calculation is displayed in Table 4.20.

Table 4.20. Calculation of customer satisfaction from scenario – an example.

<b>EXTERNAL CUSTOMER SATISFACTION</b>	Color	Vol. (ml)	Recyc. R. (%)	Deposit	
<b>Scenario 1</b>	Colorless	330	90	Yes	
Minimum adverse health/safety impacts	54	54	54	0	162
Near sale and recycle points	0	0	75.6	0	75.6
Lightness	0	84.6	0	28.2	113
Cheapness	75.6	75.6	25.2	25.2	202
Durability	0	0	0	75.6	75.6
Light reflection - protection of beverage	19.8	0	0	0	19.8
Conformance to standards	0	0	57.6	57.6	115
Easy to sort	0	0	0	66.6	66.6
Ease of recycling, reuse, disposal	24	0	0	72	96
					925

Total satisfaction levels are calculated for all scenarios and presented in Table 4.21. They are crucial, since these data are used in data envelopment analysis.

Table 4.21. Customer satisfaction comparison results.

Scenario No.	External Customer Satisfaction	Internal Customer Satisfaction	Society Satisfaction
1	925.2	1636.2	3288.0
2	970.8	1165.8	3067.8
3	976.8	1545.0	3057.0
4	864.0	1144.2	2318.4
5	901.2	1269.6	2615.4
6	938.4	1395.0	2912.4
7	909.6	1086.0	2098.2
8	946.8	1211.4	2395.2
9	984.0	1336.8	2692.2
10	915.6	1053.0	2087.4
11	952.8	1178.4	2384.4
12	990.0	1303.8	2681.4
13	853.8	1528.8	3078.6
14	899.4	1470.6	2858.4
15	905.4	1437.6	2847.6
16	792.6	1036.8	2109.0
17	829.8	1162.2	2406.0
18	867.0	1287.6	2703.0
19	838.2	978.6	1888.8
20	875.4	1104.0	2185.8
21	912.6	1229.4	2482.8
22	844.2	945.6	1878.0
23	881.4	1071.0	2175.0
24	918.6	1196.4	2472.0

#### 4.5. Environmental Data Envelopment Analysis

In the environmental data envelopment analysis, the decision making units (DMUs) are specified as design alternatives. The linear mathematical model of DEA aims to find the most sustainable scenario. The optimization model integrates the three dimensions of the sustainability and provides scientific results in assessment of the design options regarding the trade-offs.

The inputs and the outputs are selected from the crucial aspects of sustainability which are already examined by quality function deployment, life cycle assessment, and life cycle costing methodologies. Inputs are raw materials and costs, undesired outputs are emissions, and desired outputs are customer satisfaction. The data for the model are

obtained by comparisons of technical attributes and customer satisfaction performed in previous sections. Raw materials and emissions are specified with life cycle assessment in Table 4.15 and 4.17, respectively. Moreover, cost values are obtained by life cycle costing methodology in Table 4.18 whereas customer satisfactions are calculated in Table 4.21.

First of all, the data are examined, and the correlations between inputs and outputs are analyzed as displayed in Table 4.22. Correlation is not observed among inputs. However, it is found that there is strong correlation between internal customer satisfaction and society satisfaction in the desired outputs group. Another correlation is also between undesired output and desired outputs. The emission amounts are correlated with internal customer satisfaction and society satisfaction. Although one of the correlated outputs may be eliminated in the model, none of them is eliminated, since number of outputs is not very high and all outputs are crucial in sustainability.

Table 4.22. Correlations among model data.

	External Cust. Sat.	Internal Cust. Sat.	Society Sat.	Emission Amnts.	Raw Material Con. Amnts.	Costs
External Cust. Sat.	1					
Internal Cust. Sat.	0.42078	1				
Society Sat.	0.49582	0.9183	1			
Emission Amnts.	0.54598	0.95518	0.99049	1		
Raw Mat. Con. Amnts.	-0.6579	-0.8666	-0.92	-0.9356	1	
Cost	-0.3595	0.14089	0.14836	0.11073	0.01603	1

Moreover, another crucial point is the determining the correlation between inputs and outputs for deciding the data envelopment model. If the inputs are correlated with outputs, constant returns to scale is accepted, otherwise variable returns to scale is adopted. In our study, raw material as input found to be correlated with internal customer satisfaction and society satisfaction from desired outputs, emissions from undesired outputs. Additionally, the cost is not correlated with any other data. Hence, both constant returns to scale and variable returns to scale can be utilized.

Table 4.23. Results of environmental data envelopment model.

Scenario No.	Input Oriented CCR	Input Oriented BCC	Output Oriented CCR	Output Oriented BCC
1	1.0000	1.0000	1.0000	1.0000
2	0.6458	0.751	1.5485	1.0022
3	1.0000	1.0000	1.0000	1.0000
4	0.4437	0.4819	2.2538	1.1454
5	0.6997	0.7285	1.4292	1.0761
6	1.0000	1.0000	1.0000	1.0000
7	0.3022	0.3118	3.3088	1.0884
8	0.3919	0.4256	2.5516	1.0456
9	0.491	0.7171	2.0365	1.004
10	0.4186	0.429	2.389	1.0813
11	0.6025	0.6102	1.6599	1.039
12	1.0000	1.0000	1.0000	1.0000
13	0.4201	0.5033	2.3802	1.068
14	0.4281	0.472	2.336	1.069
15	0.5207	0.5469	1.9206	1.0767
16	0.2262	0.2678	4.4202	1.2491
17	0.3582	0.405	2.792	1.1858
18	0.5156	0.5556	1.9394	1.1271
19	0.2258	0.2528	4.4285	1.1811
20	0.2938	0.3149	3.4036	1.1309
21	0.2821	0.2901	3.5444	1.0831
22	0.2219	0.2467	4.5059	1.1727
23	0.2851	0.3036	3.5073	1.1232
24	0.3597	0.3674	2.7802	1.0777

The environmental data envelopment model in Section 3.3.2.2. is applied with GAMS CPLEX solver. Based on this input oriented CCR model, output oriented CCR model, input oriented BCC model, output oriented BCC model are also created and solved. The results of the models are presented in Table 4.23.

The applied models obtain the same design alternatives as sustainable. As a result of environmental data envelopment models, design alternatives 1, 3, 6 and 12 are found as the most sustainable options. The Scenario 1 and Scenario 3 are multi-way scenarios of colorless and green containers, respectively. Similarly, Scenario 6 and Scenario 12 are one-

way scenarios of same colors. Scenarios with 500 ml volume option are not attained to be sustainable.

Additionally, the correlation between efficiency scores and inputs/outputs are analyzed at Table 4.24. The results indicate that efficiency scores of input oriented models are positively correlated with outputs and negatively correlated with inputs. On the other hand, efficiency scores of output oriented models are positively correlated with inputs and negatively correlated with outputs. The reason of this correlation can be explained by the nature of objective functions. Input oriented models aim to minimize inputs whereas output oriented models aim to maximize outputs.

Table 4.24. Correlation between efficiency scores and model data.

	Desired Outputs			Undesired Output	Inputs	
	External Cust. Sat.	Internal Cust. Sat.	Society Sat.	Emission Amnts.	Raw Material Con. Amnts.	Costs
Input Oriented CCR	0.6512	0.6851	0.7317	0.7539	-0.7677	-0.4498
Input Oriented BCC	0.6839	0.7067	0.7743	0.7917	-0.7929	-0.4123
Output Oriented CCR	-0.7091	-0.7331	-0.8017	-0.8202	0.8919	0.3765
Output Oriented BCC	-0.9276	-0.6583	-0.7174	-0.7602	0.8251	0.2524

## **5. CONCLUSIONS AND RECOMMENDATIONS**

This chapter presents the conclusions based on findings of this study, contributions to the literature and finally suggestions for future research. Conclusions include the summary and the results of the thesis, and contributions emphasize the significance of the approach on sustainable product design area. Since there exists many other improvements and also broader topics related with sustainability and sustainable products, the suggestions for future research part is constructed in order to lead into other studies.

### **5.1. Conclusions**

The integration of sustainability into the product development process at all stages of a product's life leads to a new paradigm which is reflected in a new way of thinking, new application tools, and methodologies. Thus, in this thesis, we deal with modeling of sustainable product development problem. Our purpose is to develop a methodological approach to assist companies in developing and evaluating sustainable products which would also contribute to the competitive power. This objective has triggered our study to construct a three phased methodology based on life cycle view.

In the first phase of the methodology, the current product system analysis is focused, and results are debated. Processes along the life cycle duration are defined, and their inputs and outputs are assessed taking into account environment and economical dimensions with tools of LCA and LCC, respectively. Afterwards, design alternatives are considered and their assessments are performed. Customer is divided into segments in accordance with sustainability, and their requirements are analyzed with life cycle view. New design alternatives correlated with significant technical attributes are generated and compared with QFD in the second phase. Lastly, all the outputs of preceding sections are gathered, and the selection of most sustainable design is obtained by a mathematical model which is constructed based on DEA.

In order to apply the proposed methodology, a case study is conducted. Glass beverage container design and development case is analyzed in the context of sustainability. Twenty four design alternatives are generated in consideration of crucial technical attributes which are color, volume, recycling ratio and the existence of deposit system. The selected glass beverage container designs are the green and colorless ones which are multi-way with 330 ml volume option, namely option 1 and 3, and the others that are one-way with 330 ml but also with 90 % recycling rate, namely option 6 and 12. Design alternatives 1 and 3 have the least raw material consumption amounts compared with others, and emission amounts with average values in all options. On the other hand, design alternatives 6 and 12 have average raw material consumption amounts, and the least emission amounts. Costs are much less in design alternatives 6 and 12, since they are one-way scenarios, and not too much in options 1 and 3 compared with 500 ml scenarios, since they have less volume and less material consumption. Moreover, the customer satisfaction values also corroborate the selection results. Thus, as a consequence of the case study, it is proven that our proposed methodology is applicable and useful in product design and development area.

## **5.2. Contributions**

By conducting this study, we propose a new approach for sustainable product development. The systematic approach integrates life cycle view and sustainability notion to the product design and development process. The key characteristics of the developed methodology are listed in four elements:

- Life cycle viewpoint and system approach to product improvement process,
- Customer segmentation in accordance with sustainability,
- Simultaneous consideration of quality, economic, and environmental aspects in assessments of product design alternatives,
- Mathematical model employed as a decision making tool in selecting the most sustainable design option.

The triple bottom line of sustainability is integrated to product design process with quality, environmental and economical dimensions as well as with our applied tools reflecting these aspects, and customer segmentation. All elements in the methodology have relationship with each other and compose a reasonable framework for achieving sustainability. In this point of view, life cycle approach is not only employed in LCA and LCC, but rather it is adopted in QFD. As a result of this adaptation, it is observed that analyzing customer requirements in accordance with life cycle stages enhances sustainability of product attributes. Moreover, analysis of requirements is also performed in the matter of customer segmentation which includes external customer, internal customer, and society. Therefore, they are proposed as focus groups for expressing the key components of sustainability.

The selection of the most sustainable design with DEA is a newly proposed approach for sustainable product development. DEA is integrated to our proposed methodology as a decision making tool for design alternatives. In order to maintain the sustainability, the traditional DEA metric of efficiency is modified to environmental performance indicator which employs the outputs of other tools, namely, LCA, LCC, and QFD. Environmental considerations are taken into account twice for emphasizing sustainability. For instance, internal customer and society satisfaction is strictly correlated with emission amounts, and environmental DEA model considers both customer satisfaction and emission amounts.

In the aspect of environmental DEA model, there exist desirable outputs to be maximized, and inputs and undesirable outputs to be minimized. Input and output oriented models are also constructed for environmental performance indicator in the cases of constant returns to scale and variable returns to scale. It is procured that input and output oriented models indicate the same design alternatives as sustainable which also proves that our approach is in the accurate direction.

### **5.3. Suggestions for Further Research**

It is obvious that in the future, sustainable products will be ever more appealing to lots of people, and sustainability studies will be more prominent. Product design based on

life cycle perspective lead competitive advantage as well as better performance in terms of environmental and social impact. This motivation will trigger the production of sustainable products in all areas.

In this thesis, due to data limitations, we propose a very generic product in application so as to provide a basis to the methodology. As suggestion for future research, the scope can be enhanced, and more complex products could be investigated. This would also make the problem more complicated and interesting. More design alternatives can be constructed and the selection of the most sustainable design can be tougher in terms of assessing the options.

Moreover, conducting LCA, LCC and QFD studies comprehensively are not intended, but rather to know and indicate that how these three methodologies can be potentially integrated are aimed. Thus, fundamental parts of these studies are handled for addressing the simultaneous consideration of quality, environmental effect, and cost.

In the study for environmental aspect, emphasis is on determining raw material consumptions and emissions through all life cycle stages. Full LCA application is not handled, since it is out of the scope. Although our abridged LCA is restricted with inventory analysis, it is also applicable for our thesis by illustrating the raw material consumptions and emission amounts in life cycle stages. However, if it is intended it is also appropriate to imply the full methodology and calculate environmental impact categories.

Additionally, as another limitation, QFD is not also applied as a whole methodology. House of quality is the only matrix that is used in product planning phase. Other phases such as part deployment, process planning and production planning are not completed since they are very detailed and intricacy design stages. The reason of our limitation is the fact that product planning provides to know customer requirements and important product attributes, in addition to compare various design options.

Finally, for more complex problems environmental data envelopment is required to be enhanced. In this study, radial approach is adopted, and slacks of the model are assumed as zero. However, in accordance with non-radial approach, a slack based model can also be developed. It would be effective in problems which have too many design alternatives. Moreover, the number of DMUs, the inputs and outputs are crucial in terms of the correctness of the analysis. In the case of lower number of DMUs, all of them could be selected as efficient. Therefore, DEA can also be modified in such situations by bounding the weights of the inputs and outputs.

## APPENDIX A: TECHNICAL SPECIFICATIONS OF SCENARIOS

Table A.1. Height – diameter – shape specifications of containers in scenarios.

Scenario No.	Height (mm)	Diameter (mm)	Thickness (mm)	Shape No.
1	222.2	60.7	0.40	1
2	233.0	61.3	0.40	2
3	222.2	60.7	0.40	1
4	220.0	63.2	0.30	3
5	220.0	63.2	0.30	3
6	220.0	63.2	0.30	3
7	220.0	62.6	0.75	4
8	220.0	62.6	0.75	4
9	220.0	62.6	0.75	4
10	226.0	60.7	0.40	5
11	226.0	60.7	0.40	5
12	226.0	60.7	0.40	5
13	267.0	68.0	0.50	6
14	270.0	58.5	0.60	5
15	267.0	68.0	0.50	6
16	257.0	68.0	0.30	6
17	257.0	68.0	0.30	6
18	257.0	68.0	0.30	6
19	260.0	67.5	0.75	2
20	260.0	67.5	0.75	2
21	260.0	67.5	0.75	2
22	257.0	68.0	0.40	6
23	257.0	68.0	0.40	6
24	257.0	68.0	0.40	6

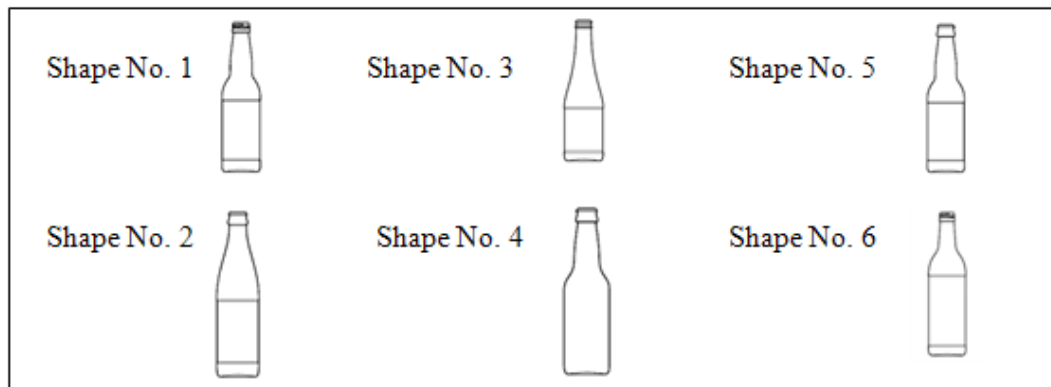


Figure A.1. Container shape options.

## APPENDIX B: LIFE CYCLE POLLUTANT AMOUNTS OF SCENARIOS

Table B.1. Manufacturing emissions of scenarios.

Scenario No.	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>2</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC (kg)	Dust(kg)
1	4.47	8741.61	0.94	22.40	0.05	1.53	1.82
2	5.90	10673.65	1.33	44.56	0.07	2.09	2.69
3	7.27	5981.84	22.95	75.84	0.05	1.48	15.45
4	15.91	26183.02	3.32	86.04	0.18	5.45	6.47
5	11.80	14971.11	2.42	71.47	0.13	4.04	4.80
6	8.74	8560.29	1.76	59.36	0.10	2.99	3.55
7	23.22	42041.78	5.19	186.37	0.28	8.25	10.61
8	17.21	31162.11	3.79	154.79	0.21	6.12	7.87
9	12.23	23097.91	2.76	128.57	0.15	4.53	5.83
10	35.02	28814.24	111.06	352.70	0.24	7.14	74.41
11	26.43	21748.41	74.34	277.36	0.18	5.39	56.16
12	19.59	16120.30	60.22	245.08	0.13	4.00	41.63
13	7.29	14252.63	1.53	36.52	0.08	2.49	2.96
14	7.71	13957.85	1.74	58.27	0.09	2.74	3.52
15	11.28	9284.86	35.62	117.71	0.08	2.30	23.98
16	28.64	47129.44	5.97	154.88	0.32	9.80	11.65
17	21.23	26948.00	4.35	128.64	0.24	7.27	8.63
18	15.74	15408.52	3.17	106.85	0.18	5.39	6.40
19	28.64	51851.53	6.41	229.85	0.34	10.18	13.09
20	21.23	38433.27	4.67	190.91	0.25	7.54	9.70
21	15.73	28487.42	3.40	158.57	0.19	5.59	7.19
22	63.04	51865.63	199.90	634.86	0.43	12.86	133.93
23	47.58	39147.14	133.82	499.26	0.33	9.71	101.09
24	35.27	29016.55	108.39	441.14	0.24	7.20	74.93

Table B.2. Transportation emissions of scenarios.

Scenario No.	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC(kg)	Dust(kg)
1	29.64	8928.03	8.53	110.06	0.50	14.90	5.64
2	39.31	3716.38	11.31	145.97	0.67	19.77	7.48
3	18.87	5684.74	5.43	70.08	0.32	9.49	3.59
4	5.15	1552.70	1.48	19.14	0.09	2.59	0.98
5	5.15	1552.70	1.48	19.14	0.09	2.59	0.98
6	5.15	1552.70	1.48	19.14	0.09	2.59	0.98
7	7.26	686.10	2.09	26.95	0.12	3.65	1.38
8	7.26	686.10	2.09	26.95	0.12	3.65	1.38
9	7.26	686.10	2.09	26.95	0.12	3.65	1.38
10	4.92	1482.98	1.42	18.28	0.08	2.48	0.94
11	4.92	1482.98	1.42	18.28	0.08	2.48	0.94
12	4.92	1482.98	1.42	18.28	0.08	2.48	0.94
13	48.32	14556.56	13.90	179.44	0.82	24.30	9.19
14	51.40	4859.88	14.79	190.88	0.87	25.85	9.78
15	30.77	9268.59	8.85	114.25	0.52	15.47	5.85
16	9.28	2794.86	2.67	34.45	0.16	4.67	1.76
17	9.28	2794.86	2.67	34.45	0.16	4.67	1.76
18	9.28	2794.86	2.67	34.45	0.16	4.67	1.76
19	8.95	846.19	2.58	33.24	0.15	4.50	1.70
20	8.95	846.19	2.58	33.24	0.15	4.50	1.70
21	8.95	846.19	2.58	33.24	0.15	4.50	1.70
22	5.91	1779.57	1.70	21.94	0.10	2.97	1.12
23	5.91	1779.57	1.70	21.94	0.10	2.97	1.12
24	5.91	1779.57	1.70	21.94	0.10	2.97	1.12

Table B.3. Usage emissions of scenarios.

Scenario No.	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	NM VOC (kg)	Dust(kg)
1	24.54	6756.25	6.46	64.38	0.50	14.86	5.99
2	34.68	9546.88	9.13	90.98	0.71	21.00	8.46
3	24.54	6756.25	6.46	64.38	0.50	14.86	5.99
4	4.27	1175.00	1.12	11.20	0.09	2.58	1.04
5	4.27	1175.00	1.12	11.20	0.09	2.58	1.04
6	4.27	1175.00	1.12	11.20	0.09	2.58	1.04
7	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
8	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
9	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
10	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
11	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
12	6.40	1762.50	1.69	16.80	0.13	3.88	1.56
13	40.01	11015.63	10.54	104.97	0.82	24.23	9.76
14	45.35	12484.38	11.94	118.97	0.92	27.46	11.06
15	40.01	11015.63	10.54	104.97	0.82	24.23	9.76
16	7.68	2115.00	2.02	20.15	0.16	4.65	1.87
17	7.68	2115.00	2.02	20.15	0.16	4.65	1.87
18	7.68	2115.00	2.02	20.15	0.16	4.65	1.87
19	7.90	2173.75	2.08	20.71	0.16	4.78	1.93
20	7.90	2173.75	2.08	20.71	0.16	4.78	1.93
21	7.90	2173.75	2.08	20.71	0.16	4.78	1.93
22	7.68	2115.00	2.02	20.15	0.16	4.65	1.87
23	7.68	2115.00	2.02	20.15	0.16	4.65	1.87
24	7.68	2115.00	2.02	20.15	0.16	4.65	1.87

Table B.4. Recycling emissions of scenarios.

Scenario No.	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	NMVOC(kg)	Dust (kg)
1	19.25	3534.63	3.41	31.27	0.39	13.25	3.16
2	30.71	5640.65	5.43	49.83	0.63	18.64	5.05
3	20.34	3735.61	3.60	33.05	2.88	12.34	3.34
4	5.58	1024.53	0.99	9.06	0.11	3.84	0.92
5	11.16	2049.06	1.97	18.13	0.23	7.68	1.83
6	16.74	3073.59	2.96	27.19	0.34	11.52	2.75
7	9.45	1735.59	1.67	15.33	0.19	5.73	1.55
8	18.90	3471.17	3.34	30.66	0.39	11.47	3.11
9	28.35	5206.76	5.01	46.00	0.58	17.20	4.66
10	5.90	1082.79	1.04	9.58	0.83	3.58	0.97
11	11.79	2165.57	2.09	19.16	1.67	7.15	1.94
12	17.69	3248.36	3.13	28.74	2.50	10.73	2.90
13	17.44	3201.66	3.08	28.32	0.36	12.00	2.86
14	40.16	7376.24	7.10	65.16	0.82	24.37	6.60
15	33.16	6090.67	5.87	53.88	4.69	20.12	5.44
16	10.04	1844.15	1.78	16.31	0.21	6.91	1.65
17	20.09	3688.31	3.55	32.63	0.41	13.82	3.29
18	30.13	5532.46	5.33	48.94	0.62	20.74	4.94
19	11.66	2140.56	2.06	18.91	0.24	7.07	1.91
20	23.31	4281.11	4.12	37.82	0.48	14.14	3.83
21	98.16	18028.38	17.36	159.48	13.89	59.56	16.11
22	10.61	1949.01	1.88	17.24	1.50	6.44	1.74
23	21.22	3898.03	3.75	34.48	3.00	12.88	3.48
24	31.84	5847.04	5.63	51.72	4.51	19.32	5.23

Table B.5. Landfilling emissions of scenarios.

Scenario No.	CO (kg)	CO <sub>2</sub> (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	NM VOC (kg)	Dust (kg)
1	0.09	15.91	0.02	0.14	0.00	0.05	0.01
2	0.09	15.63	0.02	0.14	0.00	0.05	0.01
3	0.09	15.72	0.02	0.14	0.00	0.06	0.01
4	0.53	96.86	0.09	0.86	0.01	0.32	0.09
5	0.30	55.35	0.05	0.49	0.01	0.18	0.05
6	0.08	13.84	0.01	0.12	0.00	0.05	0.01
7	0.83	142.71	0.14	1.26	0.02	0.49	0.13
8	0.47	81.55	0.08	0.72	0.01	0.28	0.07
9	0.12	20.39	0.02	0.18	0.00	0.07	0.02
10	0.78	143.56	0.14	1.27	0.02	0.53	0.13
11	0.45	82.03	0.08	0.73	0.01	0.30	0.07
12	0.11	20.51	0.02	0.18	0.00	0.08	0.02
13	0.14	25.95	0.03	0.23	0.00	0.09	0.02
14	0.17	28.88	0.03	0.26	0.00	0.10	0.03
15	0.14	25.64	0.02	0.23	0.00	0.09	0.02
16	0.81	149.45	0.14	1.32	0.02	0.49	0.13
17	0.41	74.72	0.07	0.66	0.01	0.25	0.07
18	0.14	24.91	0.02	0.22	0.00	0.08	0.02
19	1.02	176.01	0.17	1.56	0.02	0.60	0.16
20	0.58	100.58	0.10	0.89	0.01	0.34	0.09
21	0.15	25.14	0.02	0.22	0.00	0.09	0.02
22	0.94	172.27	0.17	1.53	0.02	0.63	0.15
23	0.54	98.44	0.09	0.87	0.01	0.36	0.09
24	0.13	24.61	0.02	0.22	0.00	0.09	0.02

Table B.6. Amount of other pollutants – bulk waste.

Scenario No.	Manufacturing (kg)	Recycling (kg)	Total
1	3.21	5810.18	5813.39
2	4.20	9272.04	9276.24
3	2.38	6140.38	6142.76
4	11.42	1684.11	1695.53
5	8.46	3368.22	3376.68
6	6.27	5052.33	5058.60
7	16.55	2852.94	2869.49
8	12.27	5705.87	5718.14
9	9.09	8558.81	8567.90
10	11.44	1779.82	1791.27
11	8.64	3559.64	3568.28
12	6.40	5339.46	5345.87
13	5.23	5262.84	5268.07
14	5.50	12124.98	12130.47
15	3.69	10011.50	10015.18
16	20.55	3031.40	3051.95
17	15.23	6062.80	6078.03
18	11.29	9094.19	9105.48
19	20.41	3518.62	3539.03
20	15.13	7037.24	7052.37
21	11.22	29634.03	29645.24
22	20.60	3203.68	3224.28
23	15.55	6407.36	6422.91
24	11.52	9611.04	9622.56

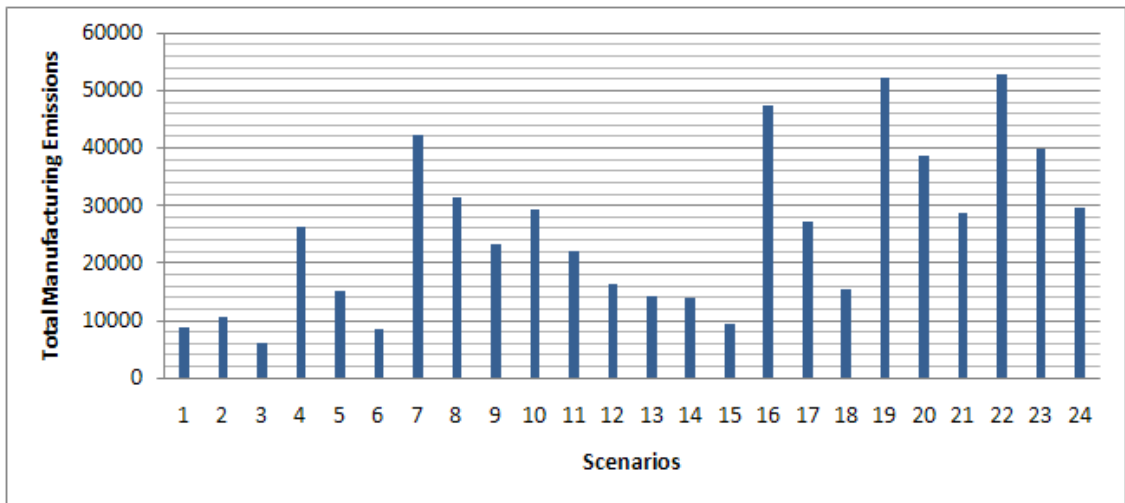


Figure B.1. Comparison of manufacturing emissions in scenarios.

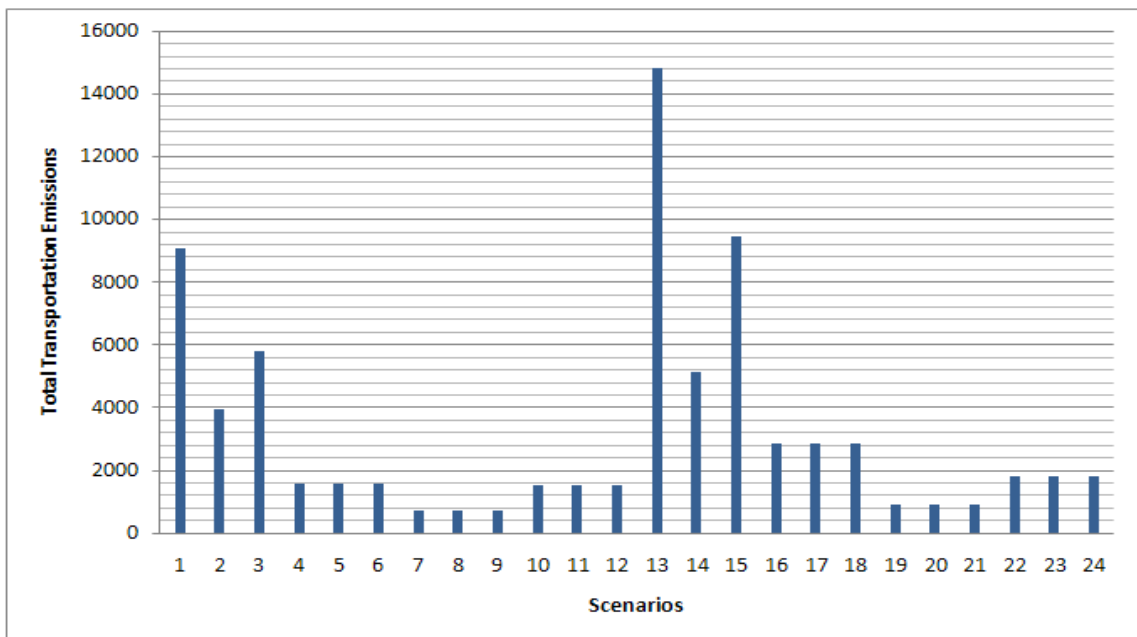


Figure B.2. Comparison of transportation emissions in scenarios.

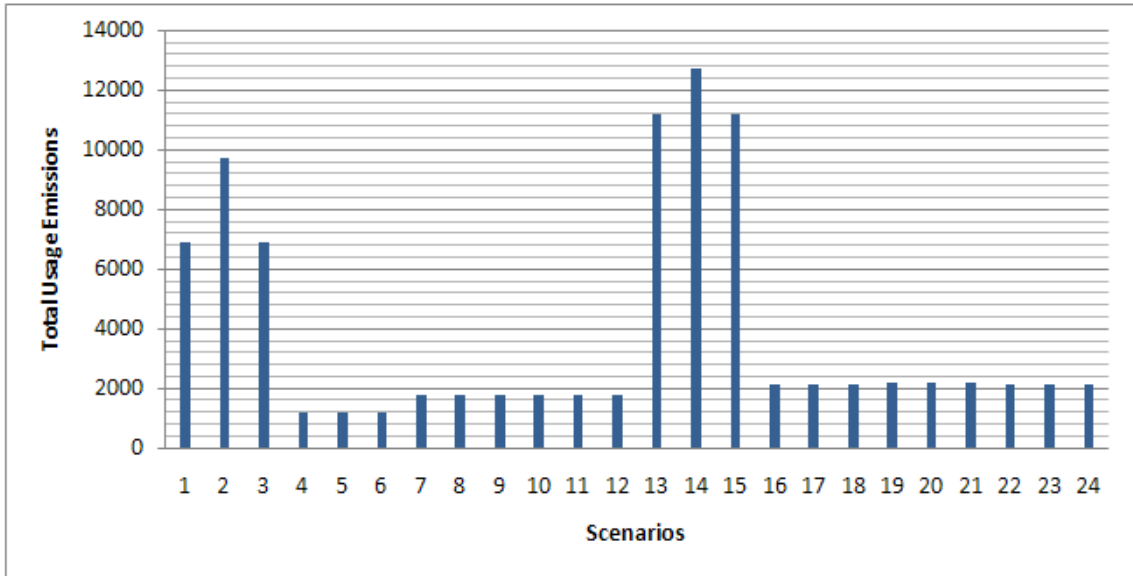


Figure B.3. Comparison of usage emissions in scenarios.

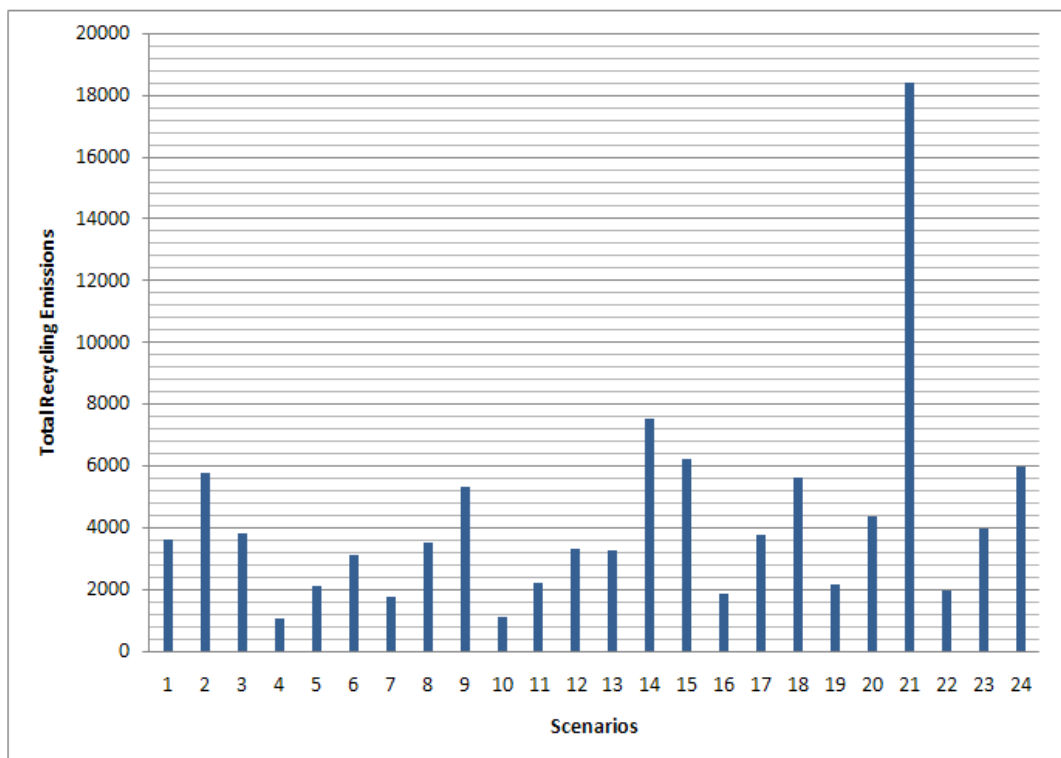


Figure B.4. Comparison of recycling emissions in scenarios.

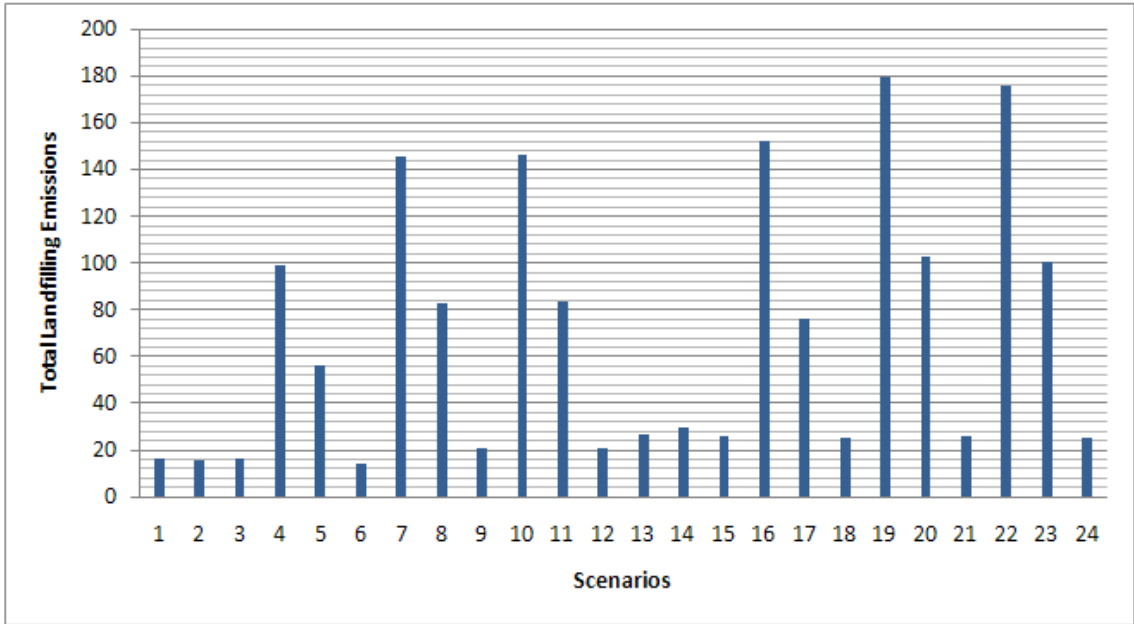
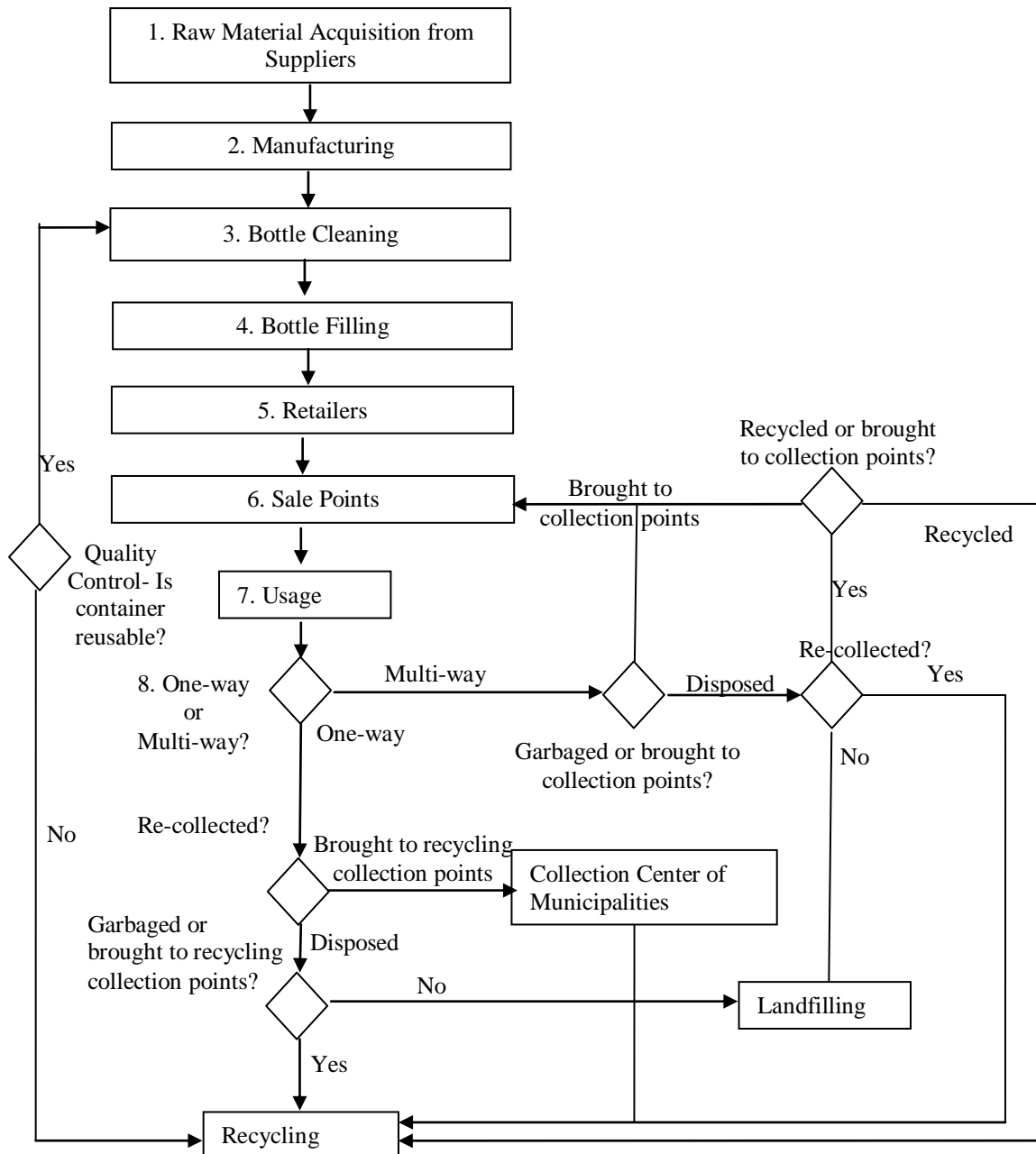


Figure B.5. Comparison of landfilling emissions in scenario.

### APPENDIX C: FLOW CHART OF THE SYSTEM

Figure C.1. Flow chart of the system.



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