DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

QUALITY FUNCTION DEPLOYMENT AND ITS APPLICATION IN SERVICE SECTOR

by

Halil AKBAŞ

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İZMİR

QUALITY FUNCTION DEPLOYMENT AND ITS APPLICATION IN SERVICE SECTOR

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We have read the thesis entitled **"QUALITY FUNCTION DEPLOYMENT AND ITS APPLICATION IN SERVICE SECTOR"** completed by **HALİL AKBAŞ** under supervision of **ASSOC. PROF. DR. BİLGE BİLGEN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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QUALITY FUNCTION DEPLOYMENT
AND ITS APPLICATION IN SERVICE SECTOR

ABSTRACT

Quality function deployment (QFD) is a holistic approach, which translates customer requirements (CRs) into engineering characteristics (ECs) for each stage of the product development to increase customer satisfaction.

Traditional QFD method can result in false solutions under uncertainty. The variability of the human judgement leads to inconsistent results in the QFD analyses. The CRs can be mistranslated into the ECs owing to the vagueness of human thoughts. The traditional QFD method can be supported with the use of fuzzy logic theory, fuzzy analytic hierarchy process (AHP) with extent analysis approach and triangular fuzzy numbers. For these reasons, related methods are applied along with the traditional QFD method to calculate the importance weights of CRs and importance values of ECs in service sector in the thesis.

A QFD approach to analyze the relationships between CRs and ECs for the biogas product development problem at a wastewater treatment facility is presented in the study. Purity, stability of content, affordability, energy efficiency and reliability are chosen as the main attributes by the engineering team. A tree diagram is drawn to show the hierarchy of CRs. The importance weights of the CRs are calculated by using fuzzy AHP with extent analysis approach. Thus, the importance values of ECs are also determined more precisely. Respecting to the results, purity is found out as the most important CR with the highest importance weight calculated by using fuzzy extent analysis. On the other hand, the required ECs are selected as purified biogas for the energy phase, pipeline system for infrastructure requirement and chemical solution for process requirement by considering the highest importance values of ECs.

Keywords: Quality function deployment, fuzzy analytic hierarchy process, fuzzy extent analysis

KALİTE FONKSİYONU YAYILIMI
VE HİZMET SEKTÖRÜNDE UYGULANMASI

ÖZ

Kalite fonksiyonu yayılımı (KFY), müşteri memnuniyetini artırmak için ürün geliştirilmesinin her aşamasında müşteri gereksinimlerinin (MG) mühendislik niteliklerine (MN) dönüştürülmesini sağlayan bütünsel bir yaklaşımdır.

Geleneksel KFY metodu belirsizlik altında hatalı çözümler verebilmektedir. İnsan yargılarındaki değişkenlik KFY analizlerinin sonuçlarının tutarsız olmasına yol açmaktadır. MG insan düşüncelerinin belirsizliği nedeniyle MN'ne yanlış çevrilebilmektedir. MG'nin önem ağırlıklarının ve MN'nin önem değerlerinin hesaplanması için geleneksel KFY metodu, bulanık mantık teorisi, derece analizi ile birlikte bulanık analitik hiyerarşik işlem (AHİ) metodu ve üçgensel bulanık sayılar kullanılarak desteklenebilir. Bu sebeplerden dolayı, bu çalışmada ilgili metotlar hizmet sektöründe MG'nin önem ağırlığını ve MN'nin önem değerlerini hesaplamak için geleneksel KFY metodu ile kullanılmştır.

Bir atıksu arıtma tesisindeki biyogaz ürün geliştirme problemi için MG ile MN arasındaki ilişkileri analiz etmek amacıyla bir KFY yaklaşımı sunulmaktadır. Mühendislik ekibi tarafından saflık, içerik istikrarı, uygun fiyat, enerji verimliliği ve güvenilirlik temel nitelikler olarak seçilmektedir. MG'ni hiyerarşik olarak göstermek için bir ağaç diyagramı çizilir. Derece analizi ile birlikte bulanık AHİ yaklaşımı kullanarak MG için önem ağırlıkları hesaplanır. Böylece MN'nin önem değerleri de daha kesin olarak belirlenir. Analiz sonuçlarına göre saflık bulanık derece analizi ile hesaplanan en yüksek önem ağırlığı ile en önemli MG olarak bulunmuştur. Diğer taraftan, MN'nin en yüksek önem değerleri göz önüne alınarak, gerek duyulan MN enerji fazı için saflaştırılmış biyogaz, alt yapı gerekliliği için boru hattı sistemi ve proses gerekliliği için kimyasal çözelti olarak seçilmiştir.

Anahtar kelimeler: Kalite fonksiyonu yayılımı, bulanık analitik hiyerarşi işlemi, bulanık derece analizi

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CHAPTER ONE
INTRODUCTION

Rapid innovations in technology, industry, trade and customer behaviors in markets stimulate institutions and companies to pursue these compulsory changes. Quality function deployment (QFD) is a method to search out customers, understand their needs and satisfy their expectations. Besterfield et al. (2003) states that customer expectations should be met and exceeded. QFD presents specific techniques to assure quality throughout each step of product development process. QFD contributes to product design, engineering and production, if an institution truly implements its technique. QFD improves customer satisfaction, reduces implementation time, promotes teamwork and provides documentation. Customer requirements (CRs) are mostly identified as the voice of the customer. It is converted to technical features, which can be deployed through product planning, part development, process planning, production planning and service industries. The overall quality of the product is constituted through this flow of relationships. By performing QFD, an institution achieves the application of the voice of the customer (VOC) in the final product or service (Besterfield et al., 2003).

The principal target of total quality management is to increase customer satisfaction. Liu & Wu (2008) states that an institution should constantly improve its products and processes to achieve the main target and QFD is a useful methodology including adequate tools to meet CRs and to increase customer satisfaction.

A holistic QFD system must deploy technology, reliability and cost aspects (Akao, 1990). As stated by Vanegas & Labib (2001), the VOC is converted into the engineering characteristics and these characteristics can be modified in order to fulfill the customer requirements. One of the main objectives of QFD is the estimation of target values of engineering characteristics. When the QFD uses empirical calculations to estimate the target values of the engineering characteristics, it might be incapable of reaching at the essential results (Vanegas & Labib, 2001).

QFD consists of two main group decision making processes. The first one is to collect the CRs from a group of customers, while the second one is to determine the relationship between CRs and technical measures. Subjective opinions create systematic problems in a group decision-making process. The vague and unclear ideas of group members lead to imprecise determination of the relationship between CRs and technical measures. A fuzzy group decision-making method can be used in QFD to overcome vagueness in group decision-making (Liu & Wu, 2008).

Both the quality and design development of any product with limited resources at competitive markets require a customer driven quality management (Kahraman et al., 2006). Kahraman et al. (2006) stated that QFD was used as an influential instrument to advance product design and quality and to supply a customer driven quality system.

QFD has been extensively used by the leading companies of the world. The first application of QFD was done by Mitsubishi Heavy Ind. Ltd. in Japan. Toyota also successfully applied QFD method at the production of mini-vans. It was seen that Toyota managed to lower fixed production costs by 60% from 1977 to 1984 and the time needed for its development by one-third by using QFD (Kahraman et al., 2006). When QFD is unsuitably implemented by an institution, then it might increase workload without creating any benefits (Akao, 1990). QFD is a complicated and demanding process including a lot of detail. Studying with large matrices can lead to calculation errors. Errors successively spread to serial stages of QFD (Besterfield et al., 2003). Therefore, QFD methodology needs predigesting and computerizing.

The houses of quality (HOQ) are a set of charts to reflect CR through engineering characteristics (ECs), parts characteristics, process plans, and manufacturing operations. A HOQ basically includes information on CRs, ECs, relationship between them and benchmarking data (Kim et al., 2000). CR is identical to ‘‘what to do” (WHATs) over the HOQ charts, while EC symbolizes ‘‘how to do it” (HOWs) over the HOQ charts. Customer satisfaction can be succeeded with the estimation of the target values of EC by considering recorded information over HOQ.

QFD involves a set of matrices mentioned as the HOQ. A HOQ matrix is the integration of matrices in order to assist the cross-functional team to turn CRs to engineering goals (Liu, 2010).

Collecting input from customers is essential for many companies to gain advantage for competing at global markets in designing a new product. QFD is a management tool, which supports each stage of product or service development process and provides assistance to the cross-functional team for concentrating on CRs (Liu, 2010).

The main idea of QFD is to concentrate on and comprehend customer needs, which are considered as the factors in the total development cycle (Bai & Kwong, 2003). QFD mainly covers four matrices. These matrices are product planning, part deployment, process planning, and production planning in order. Karsak (2004) focused on product planning matrix, which was also called HOQ. The process of QFD discloses HOQ in a matrix format. Giving response to CRs at each phase of product or service design and planning is possible with HOQ framework (Liu, 2010).

Each customer differs in behaviors and expectations from one another. Therefore, this situation should be in consideration of cross-functional team for the determination of WHATs and HOWs matrix over the decision-making process. The required information for the generation of relationship matrix between ECs and CRs has fuzzy features. The decision-making process in QFD, which is integrated with fuzzy logic approach and decision models, is tackled by some articles in literature. Karsak (2004) proposed a fuzzy multi-objective programming model to estimate the level of execution of ECs. The information used in QFD modeling was vogue and linguistic variables were assigned to represent uncertain design information. The results of the study of Karsak (2004) revealed a model focusing on ECs to maximize customer fulfillment by considering budget constraints.

To successfully execute a QFD application in practice, the input information, which is ready for QFD model, must be unrestricted and precise. However, most of the QFD problems in practice are not eligible for using conventional QFD matrices. Since, QFD problem pattern covers volatile system inputs for most of the cases. Therefore, fuzzy analytic hierarchy process (AHP) with an extent analysis approach can be used, when the conventional QFD approach cannot provide a satisfactory solution to QFD problem owing to the vagueness of the input information.

In this thesis, QFD and fuzzy AHP methods are applied to biogas development problem in a wastewater treatment facility. Biogas is produced at anaerobic digesters. It is a renewable energy resource. However, the quality of biogas is an important aspect. The methane content of biogas must be high. The quality of biogas can be improved step by step by lowering the quantity of carbon dioxide (CO_2), hydrogen sulfur (H_2S), water vapor and siloxanes. Cogeneration systems in waste water treatment facilities consume biogas for heat and electricity production. Biogas must be purified, before using it as fuel to feed engines in wastewater treatment facilities. Since, poor quality in biogas leads to corrosion, damage and very high cost of maintenance in cogeneration systems. In place of purified biogas, there are a number of alternative energy sources, which are natural gas, liquefied natural gas and compressed natural gas. The infrastructure requirements for the gas storage with available technologies in the world can be cryogenic storage, storage inside high pressure tanks, storage inside low pressure tanks and pipeline systems without storage need. On the other hand, process requirements for the improvement of gas quality are absorption process, membrane system, cryogenic process and the use of chemical solutions all around the world. The objective of this thesis is to propose a framework to analyze the relationships between what the expectations are from the energy source in gas phase and how these expectations can be achieved. The correlations between them are studied in the QFD matrix to describe the most important attributes of the energy resource and crucial engineering requirements needed to meet the expectations.

In order to solve a QFD problem, both conventional QFD and fuzzy AHP with an extent analysis approaches are maintained in this study. Conventional QFD is applied and comparison matrices are created for CRs and ECs. The importance weights are assigned and empirical formulas are applied to estimate the priorities of CRs and importance of ECs. However, human mind is not clear about coming to sensible conclusions for the importance of customer requirements. In order to overcome the limitations of conventional QFD, fuzzy AHP with an extent analysis approach is utilized to calculate the importance weights for the CRs. The weight vectors of CRs are estimated by using the extent analysis methodology and fuzzy logic rules by using triangular fuzzy numbers.

The outline of the thesis is provided as follows. In Chapter 2, literature of the QFD is expressed. Problem definition is presented in Chapter 3. Chapter 4 points out the solution methodology and formulations of conventional QFD and fuzzy AHP with an extent analysis approach in QFD. In Chapter 5, numerical example and computational results are explained. Conclusion is summarized in Chapter 6.

CHAPTER TWO
LITERATURE REVIEW

The literature on QFD has a large volume. The target values of ECs can be estimated by using systematic modelling methods as indicated by Wasserman (1993). Wasserman (1993) used a linear programming model to choose the design characteristics of a QFD planning process to meet the customer satisfaction.

Khoo & Ho (1996) proposed an approach based on the probability theory. Furthermore, a fuzzy mathematical approach was used to overcome the ambiguity in their study. The framework of fuzzy QFD was presented by the authors.

Moskowitz & Kim (1997) studied on analyses of product designs. They formulated a modelling coupled with mathematical programming approach to find out optimal product designs.

Fung et al. (1998) pointed out a fuzzy inference system to support the design selection model of target values for ECs on the basis of a fuzzy rule base. Park & Kim (1998) put forward an improved HOQ model for optimal design selection of ECs.

Kim et al. (2000) designed a QFD planning approach using fuzzy modelling with linear equations. Shen et al. (2001) executed a QFD application under fuzzy environments in their study. Fuzzification and defuzzification techniques were focused on in detail in their study. In literature, there are also studies offering combination models of fuzzy modelling and genetic algorithm for estimating target values of ECs (Tang et al., 2002; Bai & Kwong, 2003).

Buyukozkan et al. (2004) used analytic network process (ANP) and AHP to estimate the importance degrees of ECs and CRs in their study. Additionally, Buyukozkan et al. (2004) utilized triangular fuzzy numbers in the fuzzy ANP approach to be able to focus on the importance of CRs and ECs with imprecise human judgement.

Bottani & Rizzi (2006) aimed at proposing a method for the management of customer service. Their approach was built on the basis of the fuzzy QFD and it indicated how to deploy the HOQ to improve logistics processes and customer satisfaction.

Lee et al. (2008) presented an approach integrating the Kano model with fuzzy logic theory to constitute a QFD matrix. Customer requirement weights were assigned by using their approach. This integrated approach proposed a new method to optimize the product design and to rise customer satisfaction (Lee et al., 2008).

Kuo et al. (2009) applied a fuzzy logic approach for product development planning to reduce the vagueness and uncertainty in a group decision-making process. In their study, a fuzzy multi-objective model was used to consider the holistic customer satisfaction and to inspire enterprises for the production of an environmentally friendly product. Their approach was called as eco-quality function deployment (Eco-QFD) model. This model considered the environmental elements to obtain an equilibrium between environmental acceptability and overall customer satisfaction in QFD.

Liu (2010) established an approach to integrate fuzzy set theory and genetic algorithm (GA) to state a new group decision-making method with fuzzy individual preferences.

Buyukozkan & Berkol (2011) improved a framework for decision-making, in which analytic network process (ANP) was combined with QFD and zero-one goal programming models. With this approach, they tried to determine more influential ECs to create a sustainable supply chain.

Scott et al. (2013) investigated the results of the use of the integrated QFD and AHP approach by considering stakeholder requirements to evaluate potential suppliers in the UK bioenergy industry. It was thought that bioenergy suppliers in the UK could see the requirements of the stakeholders owing to the identification of the needs of stakeholders with this approach. The financial stability of the bioenergy supplier was estimated as the most important aspect. Moreover, a mixture of social, environmental and economic criteria, including experience, job creation, CO_2 emissions per unit of energy, and cost of material were the other criteria of the stakeholders in this article.

A QFD analysis is done by Servert et al. (2014) to choose the best one out of four solar energy applications for mining industry in a country. Their model is based on QFD methodology. Furthermore, Servert et al. (2014) states that related model is successfully used to rank the solar energy projects prior to selecting the best solar energy project.

CHAPTER THREE
PROBLEM DEFINITION

In this thesis, QFD methodology is investigated and an application of QFD in service industry is presented. Biogas product improvement problem at anaerobic sludge digestion systems in a waste water treatment service industry is studied and analyzed by applying QFD methodology.

Hurma Wastewater Treatment Facility (HWTF) is affiliated with Antalya General Directorate of Water and Wastewater (AGDWW). AGDWW is a public institution, which provides water and wastewater services to Antalya habitants. Therefore, AGDWW`s HWTF is selected as the application field in waste water treatment service industry to implement QFD in the thesis study. Anaerobic sludge digestion system and biogas production system are identical to each other throughout the thesis study.

3.1 Problem Definition

Waste water treatment service industry has technologically improved and reached at the level of developed countries in recent years in Turkey. HWTF is a modern facility providing waste water treatment service to the population of Antalya and clean water to the Mediterranean Sea. The information about the operations at HWTF is explained in section 3.3 in detail.

The HWTF is controlled by the AGDWW. The expenses of the waste water treatment services are spent from the budget of waste water treatment department of AGDWW. One of the important category of expenses covered by the budget is the energy costs of the HWTF. Although the anaerobic reactors at HWTF produce biogas to run cogeneration unit, which produces electrical and heat energy, and to operate boilers and exchangers for heat energy usage at sludge drying facility, the outsourcing costs of electricity and liquefied natural gas (LNG) still have the biggest share in the energy costs of HWTF. The LNG is used to cover the energy needs of combustion engines of the sludge drying facility. It is also utilized to run the cogeneration unit to produce electricity, when it is urgently needed.

LNG is the natural gas stored as a cryogenic liquid. The temperature required to condense natural gas depends on its precise composition, but it is typically between -120°C and -170°C. The advantage of LNG is that it offers an energy density, which is extending range and reducing refueling frequency, when compared to petrol and diesel fuels. However, the disadvantage is the high cost of cryogenic storage on vehicles and the major infrastructure requirement of LNG dispensing stations, production plants and transportation facilities.

Compressed Natural Gas (CNG) can be another option of energy source; however, it has not been used in HWTF yet. CNG is stored on the vehicle in high-pressure tanks from 200 bar to 250 bar. Natural gas consists mostly of methane and it is drawn from gas wells or in conjunction with crude oil production. As it is delivered through the pipeline system, it contains hydrocarbons, such as, ethane and propane as well as other gases, such as, nitrogen, helium, carbon dioxide, sulfur compounds, and water vapor. A sulfur based odorant is normally added to CNG to facilitate leak detection. Natural gas (NG) is lighter than air and thus it will normally dissipate in the case of a leak, giving it a significant safety advantage over liquefied petroleum gas.

NG might be the best option for HWTF, since it can be carried to HWTF through pipelines. However, the national pipe line projects have not been completed in Antalya and energy transmission lines of NG have not been connected to the HWTF in Antalya. Therefore, the increase in the biogas use at HWTF seems to be the remedy to relieve the budget. The quality of the biogas is improved with the increase in the methane (CH_4) content and the decrease of the CO_2, H_2S, siloxanes, etc. contents. The desulphurization unit at HWTF is used for removing H_2S from biogas content as mentioned in section 3.3. The scrubbers are established in the desulphurization unit and the water and sodium hydroxide (NaOH) solution is used in the scrubbers to purify the biogas from its H_2S content at HWTF. After passing through the desulphurization unit, the biogas is stored in biogas tanks prior to being used in the combustion engines of sludge drying facility or cogeneration unit. However, there are some technical constraints stopping the use of biogas as the energy source at HWTF. It is seen that the scrubber system at the desulphurization unit is practically not efficient to lower the H_2S quantity of biogas to required levels at HWTF. Furthermore, the high quantity of H_2S content of biogas leads to corrosion and mechanical problems at combustible engines. This situation creates additional maintenance, spare part and labor costs, while the waste of biogas energy and time and the disruption of works are the big losses of the institution on the other side. Therefore, an alternative technological solution can be investigated to find a consistent remedy for the purification of H_2S content of biogas. Apart from H_2S, it is suggested that the other ingredients of biogas should be considered to lower the levels of the CO_2, siloxanes, and other contents as well. The modern and actual systems for decreasing the levels of especially CO_2 and siloxanes and other contents in the biogas should be researched. With this way, the biogas product improvement at HWTF can be achieved.

The problem, which is investigated in this thesis, has the following structures:

1. The QFD analyses aim to investigate alternative energy sources in the gas form to relieve the budget by decreasing the cost of energy at the waste water treatment service industry. The biogas product development is described as the goal of the QFD model and it is evaluated in the related QFD analyses.
2. The hierarchy of CRs is constituted by taking the ideas of the engineering team at the waste water treatment service industry. The hierarchy of the CRs is determined in the tree diagram and it is put into the left wall of the HOQ. Furthermore, the hierarchy is indicated in the HOQ as primary and secondary categories of CRs.
3. The ECs are placed at the ceiling of the HOQ. Their internal correlation is investigated to be able to see any possible negative or strongly negative correlations.
4. The ECs are evaluated in the QFD analyses as well. This is important, since the biogas product development is closely related with their results. The technical requirements are evaluated to understand the most convenient gas phase for lower energy costs at the wastewater treatment service industry.

5. The relationship between ECs and CRs are searched and a matrix is established by considering the scales of strong, medium and weak with 9, 3 and 1 coefficients in order.
6. The imprecise human judgement leads to subjective decisions and it might prevent useful results of QFD analyses. Fuzzy logic approach is utilized in the QFD analyses.
7. The importance weights of CRs influence the ECs importance values. Therefore, imprecise human judgement deciding the importance weights of CRs is tolerated with fuzzy AHP with extent analysis approach.
8. The pairwise comparison for the hierarchy of attributes (CRs) can be measured by using a scale, such as, equally, moderately, strongly, very strongly or extremely.
9. The calculation rules for addition, multiplication, taking invers, etc. of fuzzy logic theory are used for the application of fuzzy extent analysis approach. The engineering team members subjectively assigns the fuzzy numbers to create a pairwise comparison matrices. Then, fuzzy comparison matrices are formed by calculating the average of the fuzzy numbers for the upper diagonal part of the matrices and subsequently by finding the inverses of the average fuzzy numbers to obtain the lower triangular part of the matrices.
10. The biggest eigenvalue, the consistency index and the consistency ratio of the fuzzy comparison matrix are calculated to check whether the judgements of the engineering team members are consistent or not.
11. By using the fuzzy extent analysis method, the satisfaction degree of an object to achieve the goal is researched.
12. The fuzzy synthetic degree value of each CR is calculated by considering the elements in the same row of the fuzzy comparison matrix with the related formulations.
13. The weight vector of each CR is calculated at the end of the fuzzy extent analysis approach. The minimum value in the weight vector of each CR category is chosen. Then, related weight values are normalized and the weight vector of CRs is attained.
14. The weights of CRs are put into the related cells of the HOQ matrix.

15. The comparison values of CRs and ECs in the HOQ matrix for the categorical CRs are multiplied with the importance weights of the related CR category and added to each other to find out the importance value of each EC.

The importance weights of CRs and the importance values of ECs are calculated to use them in the analyses for biogas product development problem by applying the fuzzy extent analysis approach and quality function deployment methods together for more accurate results in this thesis.

3.2 Biogas Production System

Energy is one of the crucial production factors for maintaining profitable and sustainable operations in industry and service sectors all around the world. Industrialization and modernization oblige humankind to find alternative energy sources to ensure continuity in energy supply, to reach minimum energy costs, and to attain environment friendly outcome of energy usage.

Over the last two decades, the burning of fossil fuel led to approximately 75% of human-caused emissions (United States Department of Energy, 2014). It is indicated by World Bank (2013) that carbon dioxide emissions stemming from the burning of both fossil fuels and the manufacture of cement were approximately 3.5 and 4.2 metric tons per capita, respectively in 2004 and 2010 in Turkey. Nevertheless, these indicators were around 5.0 and 5.3 metric tons per capita respectively in 2004 and 2010 in developing countries of Europe and Central Asia. New technologies should be developed by countries to lower fossil fuel`s carbon emissions in order to categorize fossil fuel as a clean energy source. Every country should perform strategic investments to shift into a cleaner, domestic and more secure energy sources, such as, solar, wind, geothermal and bioenergy.

Biomass is one of the most promising renewable and clean energy sources. It is converted to the form of methane gas, ethanol fuel or biodiesel fuel through digestion process to produce energy for generating and providing electricity and heat to end users. According to the result of a study of The Organisation for Economic Co-operation and Development in Figure 3.1, the percentage of renewable energy supply of Turkey in contribution to the total primary energy supply in 2011 was 11.1%, which was higher than the average of The Organisation for Economic Co-operation and Development countries by 7.8% (The Organisation for Economic Co-operation and Development [OECD], 2012).

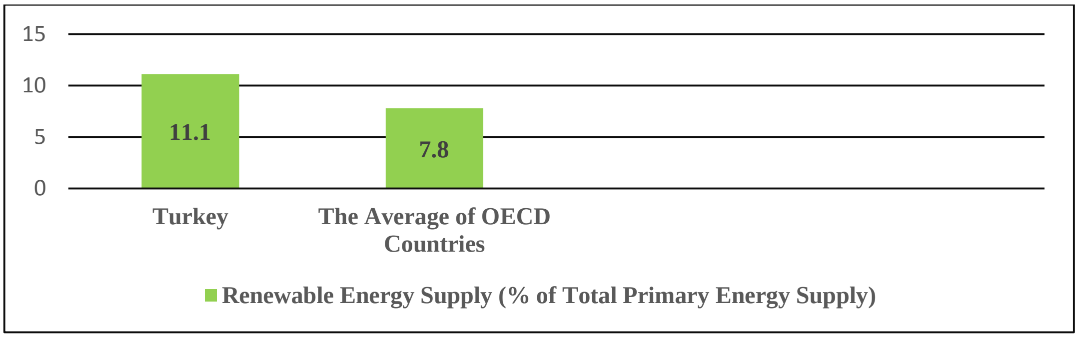

Figure 3.1 Renewable energy supply (% of total primary energy supply)

On the other hand, another study, which is done by World Bank (2013), shows that combustible renewables and waste as a percentage of total energy in Turkey were measured as 4.8% in 2009, 4.3% in 2010, 3.3% in 2011 and 3.4% in 2012 and have been slightly declined from the year of 2009 (World Bank, 2013).

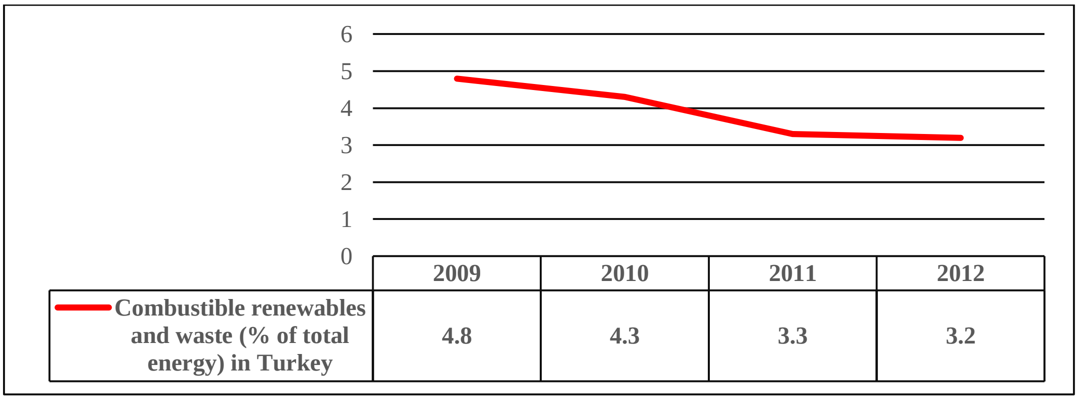

Figure 3.2 Combustible renewables and waste (% of total energy) in Turkey

It is obviously understood from Figure 3.2 that the widespread production of renewable energy sources in Turkey has to be increased to be able to supply the renewable and clean energy demands today and in the future.

Biomass power plants exist in over 50 countries around the world and supply a growing share of electricity. European countries, for example, Austria with 7%, Finland with 20%, and Germany with 5% of the renewable energy generation, are expanding their total share of power from biomass (Banos et al., 2011).

Kahraman & Kaya (2010) performed a study to propose a multi-criteria decision-making methodology to choose the best energy policy among alternatives. Wind energy was determined to be the most appropriate energy resource to utilize and invest in Turkey. On the other hand, the solar energy and bioenergy have been chosen as the second and the third important renewable energy sources, respectively in their study. It is suggested that the Turkish government should subsidize the investments especially in wind energy, solar energy and bioenergy sectors (Kahraman & Kaya, 2010).

Turkey`s electricity generation depends mostly on non-renewable energy sources. With respect to the statistical indicators of Turkish Statistical Institute (2014), the percentage of electricity generation from renewable energy and wastes in 2012 is only 3% of the total electricity generation in Turkey. As can be stated by the statistical indicators of Turkish Statistical Institute (2014), the rest of the electricity generation is obtained by combusting non-renewable energy sources, e.g., coal with 28%, natural gas with 44%, liquid fuels with 1% and hydro energy with 24%. The statistical data is seen in Figure 3.3.

As bioenergy is a promising renewable energy resource, bioenergy production system at a wastewater treatment facility must be optimally controlled. Then, electricity generation by consuming bioenergy at waste water treatment facilities can be efficiently achieved at maximum level. As stated by Berktay & Nas (2007) in their study, anaerobic digestion is a very cost effective and environmental friendly process for the stabilization of sewage sludge at municipal wastewater treatment plants. By using anaerobic digestion process, bioenergy, which is in the form of methane gas, is produced to cover the energy needs of the wastewater treatment plants.

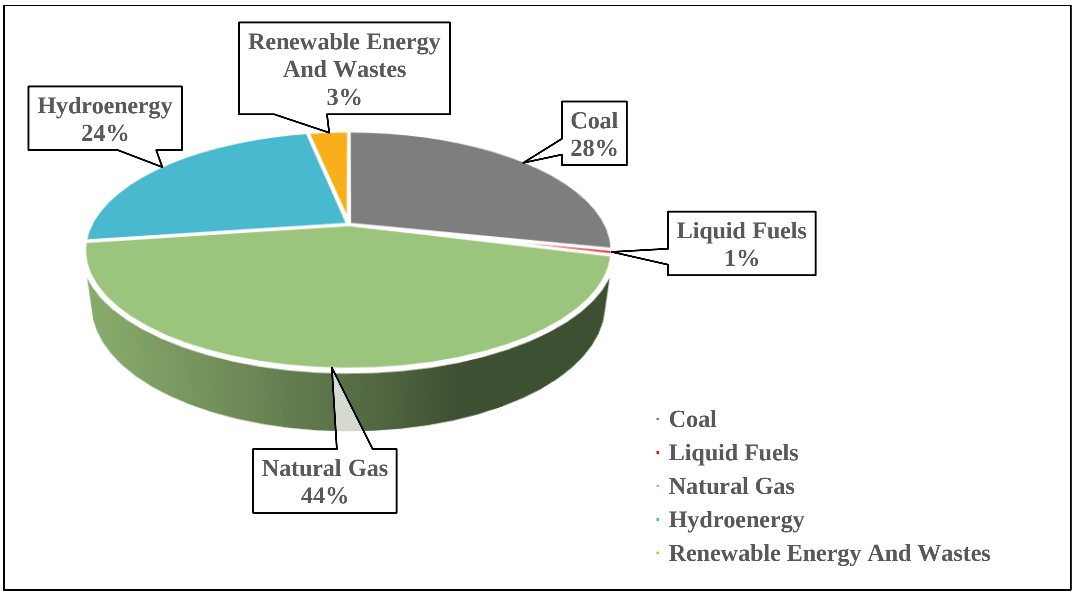

Figure 3.3 Electricity generation and shares by resources in Turkey in 2014

The use of biomass as the source of energy has been enhanced and special attention has been paid to biomass gasification particularly at wastewater treatment facilities in Turkey in recent years. Biogas can be described as a by-product of both fermenting solid and liquid biomass at waste water treatment facilities and it can be converted to heat and electricity energy by the combustion engine of a cogeneration system. Bio-gasification, i.e. anaerobic digestion, is a well-known sustainable option for the management of organic solid wastes and sludge. The produced biogas is a valuable biofuel for the replacement of fossil fuels in various technical applications, e.g. heating, electricity, and transport fuel (Kymalainen et al., 2012).

3.3 The Facility

The data used in this study is provided by AGDWW and is obtained from Hurma Wastewater Treatment Facility (HWTF) in Antalya, Turkey.

HWTF receives municipal wastewater and storm water from sewerage system of the western part of Antalya metropolitan city and maintains wastewater treatment services for Antalya`s population. HWTF serves for the population of 1.400.000

people. Wastewater arrives at the HWTF with the flow of 210.000 cubic meters per day to be discharged back into Mediterranean Sea after treatment.

HWTF has modern technology treatment equipment and systems. HWTF includes preliminary treatment units, bio-phosphorus reactors, aeration tanks, primary clarifiers, sludge thickening units, sludge dewatering units, final clarifiers, sludge digesting units, sludge returning stations, blower and generator stations, odor control units with either chemical solutions or bio filters, sludge, biogas and chemical solutions storage tanks, flare system unit, desulphurization unit, sludge drying system unit, cogeneration unit, Supervisory Control And Data Acquisition (SCADA) system unit, disinfection and discharging units. The wastewater and sludge flow through underground pipelines, which are equipped with flow meters and valves, between HWTF units.

The influent wastewater is moved by intermediate pumps from primary clarifiers to aeration tanks. There are two aeration tanks in the HWTF. Air is provided by four turbo blowers with maximum capacities of 25000 newton cubic meter per hour, and it is dissolved in the water by hundreds of diffusers located at the bottom of each aeration tank. Dissolved oxygen quantity of waste water is continuously measured by oxygen meters. Microorganisms, which live in the activated sludge, use dissolved oxygen to break down the organic matter in the water. After aeration, the wastewater enters eight cylindrical clarifiers in which microorganisms and other products can clump together and settle to the bottom, along with the remaining suspended solids. Some of the settled sludge are returned to the aeration tanks to provide a continuous resource of microorganisms for activated sludge process, and the remainder is sent to anaerobic digesters to produce biogas. The water from the eight final clarifiers is disinfected by adding chlorine and then discharged into the Mediterranean Sea.

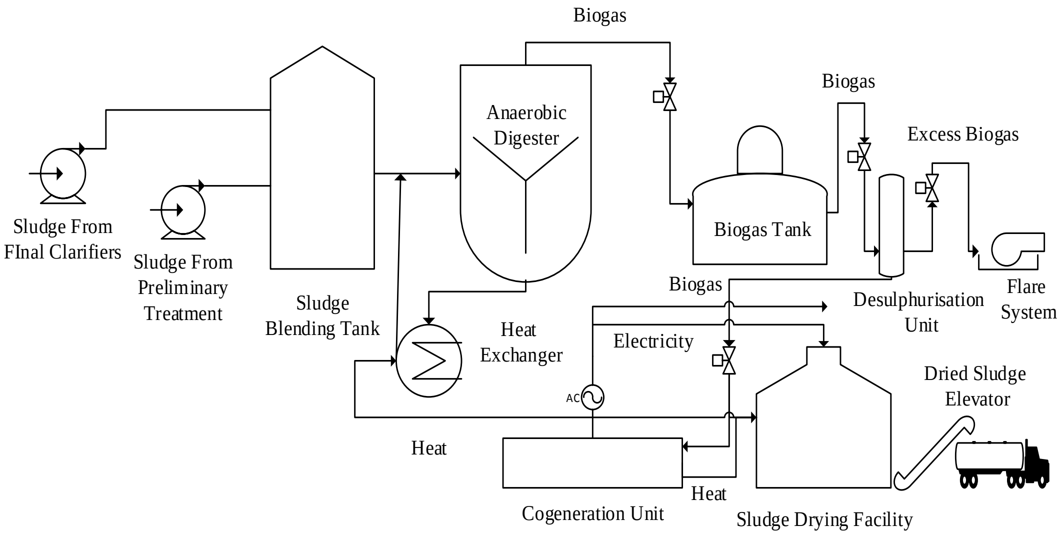

Figure 3.4 Biogas production system at HWTF

Primary residual sludge with solid content from 3% to 5% and secondary residual sludge with solid content from 0.8 % to 1% are delivered into the sludge blending tanks. The blended sludge is condensed by thickeners and its solid content increases to 5%. Then, thickened sludge goes to four anaerobic digesters. Only one digester is in practical use, while three digesters are kept as stand-by for future needs. Anaerobic digesters are used for the stabilization of biological sludge. Sludge digestion process is carried out under anaerobic and mesophilic conditions. The mesophilic bacterium group includes fermentation, acid and methane bacteria, which undertakes the task of digesting sludge. Organic matters are decomposed in anaerobic digesters at 35°C. Each anaerobic digester is 26.90 meters in height, 23.30 meters in diameter and 9000 m^3 in volume. The digesters reduce the organic content of the sludge to easily dewater it before disposal. Digested sludge is carried to the sludge dewatering unit through pipelines. Residual sludge and digested sludge mixture are condensed by sludge dewatering equipment to increase sludge solid content to 25%. Finally, dewatered sludge with solid content of 25% is sent either to sludge drying facility or to disposal area.

The sludge is heated approximately at 35°C to generate methane gas. Under the specific temperature around 35°C in the mesophilic reaction, the microorganisms residing in the reactor convert the organic wastes to biogas, which mainly consists of methane and carbon dioxide (Tay & Zhang, 1999). The generated biogas at HWTF is first stored in two biogas storage tanks with 2600 m^3 in volume each to meet peak usage demand. Then, it is used to power co-generation unit. The heat generated in the gas combustion system is also used to control the temperature of the sludge heat exchangers of both anaerobic digesters and sludge drying facility. The excess biogas can be combusted in the flare unit with the capacity of 2000 cubic meters per hour. The process diagram of biogas production system at HWTF is shown in Figure 3.4.

Biogas, which is produced in the wastewater treatment facilities by digesting sewage sludge, is a crucial source of renewable energy. It is produced from anaerobic biodegradation of biomass at wastewater treatment plants in the absence of oxygen and the presence of anaerobic microorganisms. The digestion process performs in anaerobic digesters at temperatures around 35°C in the wastewater treatment facilities. Biogas content mostly includes CH_4 gas with typical range between 40% and 70%, and its heating energy value is between 15 and 30 MJ/Nm^3. Biogas can be transformed into both heat and electricity energy by a combustion engine. Biogas is stocked in biogas tanks and carried inside pipelines by compressing in gas blowers to feed the combustible engines, when it is needed (Tippayawong & Thanompongchart, 2010).

The purity of biogas is achieved by removing CO_2, H_2S and water vapour from its content at desulphurization unit in HWTF. In all cases, the quality of biogas depends on both its CH_4 content and its purity. When CO_2 presence in biogas increases, the energy content of biogas lowers. This situation can be avoided by clearing CO_2 content of biogas to improve the CH_4 %. H_2S is a pollutant, which exists with the quantity of 100 to 10000 ppm, in biogas. Combustion systems are exposed to corrosion with a high degree, when the biogas is used in combustion engines without removing its H_2S content (Tippayawong & Thanompongchart, 2010).

3.4 The Worldwide Use of Biogas

Biogas is produced by the anaerobic sludge digestion process. Therefore, it is a clean and environmentally friendly energy source. However, it involves just about

55% to 65% of CH_4 at most. Other contents are 30% to 40% of CO_2, some amount of H_2O vapor, residuals of H_2S and H_2, and possibly other pollutants, for example, siloxanes.

The energy content of the biogas should be increased. Furthermore, the biogas can be transported, if it is economically viable. The biogas can be compressed and stored in gas cylinders or connected to a gas network. The biogas is used in the production of heat and steam energy, sludge drying facility and the electricity cogeneration unit. The biogas usage as a renewable energy source must be accompanied with compulsory rehabilitating requirements and relevant techniques (Appels et al., 2008).

In order to utilize biogas efficiently, CO_2 and other pollutants needs to be removed. This removing process also helps to refine and improve biogas quality. The heating energy value of biogas is estimated by its CH_4 content. The higher heating value of biogas supports the vapor condensation within combustion engine (Appels et al., 2008).

Existence of oxidized sulfur and H_2S along with H_2O are corrosive with most metals and their responsiveness is raised by growing temperature, mass and pressure (Appels et al., 2008).

The biogas production unit must utilize filters with the net size of 2 to 5 mm. The use of filters will render biogas cleaner with the residual amount of fine particles in the gas and clear the content of droplets of water or foam (Appels et al., 2008).

Worldwide, biogas is mainly used in combined heat and power (CHP) applications. The biogas is burnt by using gas burners to switch on combustion engines. The rate between air and gas can be adjusted considering the quality of the biogas and the pressure can be kept between 8 and 25 mbar. The quantity of H_2S should be lower than 1000 ppm (Appels et al., 2008).

Biogas is conveniently used as the energy source of CHP systems. Gas turbines, e.g., micro-turbines with 25 to 100 kW engine power, large turbines with around 4100 kW engine power, etc., have been used in practice, since they provide advantages, for example, low emission, high efficiency in comparison to combustion engines and low maintenance cost. Combustion engines are also practically used with CHP units very much. Spark-ignition and dual fuel engines are the members of the group of the combustion engines. Dual fuel engines can be turned on by using diesel fuel as well. The use of diesel injection for dual engine is economically not feasible and it causes high emission, whereas it can be chosen as an option in small scale facilities by considering its highly efficient power generation and feature of easy engine start up. Spark-ignition engines can be stoichiometric or lean-burn engines and they are integrated into the CHP systems with higher sizes. Fuel cell is another option and it can be considered as small-scale power plant of the future, This type of systems are able to provide very high efficiency levels along with low emission. The use of biogas is especially an interesting idea to feed the fuel cells. As, the CO_2 content of biogas has the function of carrying heat (Appels et al., 2008).

3.5 Biogas Product Quality Improvement Technologies

The quality of biogas product must be at a required level. A standardization of biogas product quality is necessary for the efficient system operation. Therefore, the equipment, e.g., spark-ignition engine, fuel cell, etc., require a biogas product quality improvement.

3.5.1 Carbon Dioxide Removal

CO_2 removal helps biogas quality upgrade, since it leads to higher heating value. In the event of the CO_2 removal operation, it is crucial to avoid from any possible loss of CH_4 gas because of both economic and environmental reasons. The removal techniques are called absorption, cryogenic separation and membrane separation (Degreve et al., 2001).

3.5.1.1 Absorption Process

This process can lead to that both CO_2 and H_2S are cleared at the same time. Related to the water scrubbing system, if some amount of the sulfur accumulate in the water, then it causes corrosion problems in the system. Furthermore, H_2S creates emission problem. Therefore, CO_2 should be removed, after H_2S is cleared in the system. On the other hand, it is also possible to use organic solvents to eliminate the residual CO_2 and H_2S. However, organic solvent application creates extra operational costs and its application is also difficult (Appels et al., 2008).

CO_2 is removed by using active carbon filters. The design and operation of this type of systems are not difficult. However, it is an expensive process, it requires high pressure and temperature stability and needs dry biogas by removing the water vapor.

3.5.1.2 Cryogenic Separation

This method is applicable by considering that the boiling points of CO_2 and CH_4 are -78 °C and -160 °C respectively. The cooling of biogas up to the boiling point of CO_2 removes CO_2 as liquid. This method has very high investment and management costs. The test results in Europe and the USA indicate that more than 97% pure CH_4 can be produced (Deublein & Steinhauser, 2008).

3.5.1.3 Membrane Separation

The idea is that the raw biogas is transported through a thin membrane, but some of its contents are retained. Each content moves with the effect of difference in partial pressure over the membrane. For high methane purity, permeability must be high. Acetate-cellulose polymer solid membranes have permeability for CO_2 and H_2S up to 20 and 60 times the value for CH_4. However, high pressures up to 25 bar are necessary for the process. However, there is a maximum pressure which the membrane can resist and some methane losses can occur. If the permeability is used in a CHP unit, CH_4 loss can be recovered (Degreve et al., 2001).

3.5.2 Removal of Water

Biogas includes water vapor, when it is released from the anaerobic digester. Drying process should be applied to biogas to decrease its water vapor content. The condensation of water is ensured by refrigeration process. The biogas is compressed prior to cooling to take it to higher dew points. Absorption on the application of silica gel executes low dew points when needed. Another way of removing water vapor can be the suction in glycol or hygroscopic salts (Appels et al., 2008).

3.5.3 Removal of Hydrogen Sulfur

The condition of sewage sludge influences the content of H_2S in biogas. The suitable condition of sludge restricts the H_2S content of biogas. When Fe^{3+}salts are put into the sludge, it helps keeping H_2S level inside biogas below 150ppm. However, there is a limit of Fe^{3+}addition into the sludge in order to avoid from the restriction of biogas formation (Appels et al., 2008).

H_2S can be removed by using activated carbon filters. Microorganisms, which are called the Thiobacillus family, exist in the sludge. These bacteria oxidize sulfides in the biogas. The addition of oxygen or air directly into the digestion chamber to achieve the desulphurization of biogas is necessary to reduce the level of H_2S to less than 50 ppm. The amount of oxygen added into the biogas is around 2% to 6 % of the volume of the air content of biogas. The level of air addition into biogas must be controlled very carefully not to create lack of safety. As, methane gas is explosive in the range of 5% to 15% air content (Kapdi et al., 2005).

The use of bio filters is another option for removing H_2S. The bio filters are loaded with plastic forms. These plastic forms are fixed to microorganisms for desulphurization. The air is added to the system at the volume of 5% to 19%, before biogas enters to the system. Biogas flow encounters with the flow of liquid in the system. The H_2S level can be reduced to 50 ppm to 100 ppm. As another option, the scrubbers are also practically used by feeding NaOH solution in the system to lower the level of H_2S content of biogas (Appels et al., 2008).

3.5.4 Removal of Trace Gases

Siloxanes can be present in the biogas. Since, siloxanes exist in the wastewater and are not degraded in a wastewater treatment plant. The siloxane concentrations are between 30 and 50 mg/m^3 in biogas (Dewil et al., 2006).

The siloxane content of biogas creates abrasive coatings over the surface of the equipment, which touch with biogas over combustion. Serious engine failures and damages occur owing to the coatings. Spark-ignition engines face with crucial problems, because they just use biogas as energy source (Appels et al., 2008).

The most frequently used method for taking siloxanes away is using activated carbon filters. Biogas involves H_2S, siloxanes and organic matters. The adsorbent will keep water vapor and other pollutants, so the life of adsorbent can be very short. In practice, change of activated carbon might be needed every week and its cost should be analyzed very well. Other possible adsorbents, which are molecular sieves, polymer pellets and silica gel, can be considered as other alternative absorbents. Silica gel can be used for drying biogas at the same time. Therefore, it seems that it might be a cost effective absorbent choice in industrial applications (Schweigkofler & Niessner, 2001).

The cryogenic condensation method can be used to separate siloxane from the biogas. This method is a quite feasible, but an expensive choice. When the temperature of the biogas is decreased, a condensation of siloxanes is constituted (Appels et al., 2008). On the other hand, chemical solutions` usage can reduce the siloxanes` quantity. Sulfuric, nitric and phosphoric acids or sodium hydroxide are suitable for clearing siloxanes from biogas content. However, the removal efficiencies of this method are might be rather low (Schweigkofler & Niessner, 2001).

3.6 Secondary Data Analysis

In scientific studies, researchers can design their own studies according to the characteristics of the samples and the subject of their researches. They could gather their own data, overhaul and use them in different time periods.

On the other hand, the method of individual and independent data collection has become difficult. Particularly, higher research budgets, limited time periods and possibilities to reach larger samples are the conditions, which make scientific researches harder to implement. At the same time, sample researches and data might be required to interpret the new research and to reveal significant results. For this reason, secondary data analysis has started to attain a place in modern researches (Kiecolt & Nathan, 1985).

Secondary data analysis could give a chance to the researcher to save from time and to use higher level and creative analysis techniques. A researcher would obtain larger demographic data, which he or she could not have them on his or her own. Today, with the help of technological developments, many important, expensive and useful data can be obtained easily through the internet and this situation enables secondary data analysis as a research method.

One of the most important advantages of secondary data analysis is that it provides savings to the researchers. These savings could be effective in many sources of the research, such as, cost efficient budgets, in a short span of time, with less number of people employment.

For those reasons explained above, secondary data analysis as a research method is decided to be used in this research. In addition to them, the reliability of AGDWW as a public corporation is another important reason to select this method. Data used in the study are not easy to personally obtain, so the professional team of AGDWW and their higher quality measurement devices are the first causes of this selection.

CHAPTER FOUR
SOLUTION METHODOLOGY

The combination of classical QFD method and fuzzy AHP with an extent analysis approach is applied for the biogas product development problem solution in wastewater treatment service industry in this thesis. Both models are put into the problem solution to achieve more consistent outputs. When the QFD is used with its own methodology, the HOQ matrix capability for estimating the crucial CRs and ECs to increase the attributes of the related product, service, etc., can be insufficient. As, QFD approach is based mostly on human judgement. The precise ideas commonly cannot be received from the QFD team members.

The team members can have distinct ideas for HOQ matrix creation. The unclear ideas of team members can be stabilized with fuzzy extent analysis method. This thesis includes the HOQ structure involving CRs weight vector calculated by fuzzy extent analysis method. The fuzzy logic approach helps for the sorting out this inconveniency in determining explicitly the importance weights of CRs and then explicitly the importance values of ECs.

The approach presented in this thesis consists of independent HOQ matrix building and fuzzy extent analysis models of the total system of biogas product development problem at waste water treatment service sector. Each approach develops its own solution procedures, but HOQ model uses the outcome of fuzzy extent analysis method to solve biogas product development problem.

The importance weight vector is obtained as an output from fuzzy extent analysis model, which is applied with the consideration of its theorems, rules and formulas. The weight vector for CRs is used as input for the HOQ methodology in the calculation of importance values of ECs. Then, output of the HOQ approach is found out as the importance value vector of ECs.

In this thesis, the QFD methodology is carried out with the contribution of the fuzzy logic formulations and fuzzy extent analysis approach to add more precise calculation ability for finding out the weight vector of the CRs. The weight vector is used in the HOQ chart for attaining the importance value of ECs of biogas product development problem. The related formulations and solution methods of QFD and fuzzy extent analysis are separately indicated in the following sections.

4.1 Quality Function Deployment

4.1.1 The Voice of the Customer

The voice of the customer (VOC) is described as the words, sentences and expressions done by customers for describing their expectations. The main focus of QFD is based on customer expectations, so the amount of research for finding out the customer expectations should be kept at high levels. The initial planning phase of the QFD framework intends to take more time, but the reduction of overall time spent for new product`s development satisfying customer expectations is achieved. QFD is basically organized by considering that the product`s features are directed by customer expectations. It can be thought that QFD starts with marketing side of the new product`s development. Surveys can be done, complaints can be considered and consultants` advices can be taken to determine customer expectations. Customer information can be solicited, unsolicited, numerical, qualitative, structured or random. Moreover, customer expectations are fuzzy. QFD promotes teamwork and QFD team is responsible to correctly translate CRs into technical feature of the new product. The team must add a feature, which is unexpected but appreciated by customers, to the product to meet the expectations of the customers.

4.1.2 Organization of Information in QFD

The collected information related to customer expectations must be processed by the QFD team. Management tools, for example, affinity diagram, interrelationship diagram, tree diagram, matrix diagram, prioritization matrix, etc., are useful tools for process development, cost lowering, quality policy deployment and new product development (Besterfield et al., 2003).

The affinity diagram is used especially with large data sets to organize them by depending on their natural sub-groupings. It is not suggested to employ affinity diagrams for simple problems. A team of six to eight members is expected to absorb the ideas and constitute affinity diagrams. The objectives are briefly put into a sentence in the first step. Secondly, the phrases are evaluated with a brainstorming meeting and the ideas about each statement are written over a paper. Then, the statements are classified into sub-groups. Finally, the most descriptive statement of each sub-group is chosen as the caption. The affinity diagrams are helpful to produce a large number of creative ideas and logical sub-groups of them for understanding the problem`s details.

4.1.3 House of Quality

The principal planning tool of QFD is HOQ. The main design of QFD is similar to the framework of a house (Besterfield et al., 2003). The divisions of HOQ are as seen in Figure 4.1. QFD is a method for transferring CRs and expectations into ECs to be able to increase customer satisfaction (Buyukozkan et al., 2004). Buyukozkan et al. (2004) states that the HOQ is a matrix maintaining a notional road map for the design process and it is used by QFD as a framework for understanding CRs and determining the importance degrees of ECs to fulfill them.

The parts of the house are outside walls, inside walls, ceiling, roof and ground. The outside walls of the house are placed both on the left and right. The left wall is for the customer expectations, while the wall on the right is for prioritized customer expectations. The left wall covers the VOC. The wall on the right side can be used as a planning matrix including customer competitive assessment, importance degree to customer, target value, scale-up factor and sales point. The ceiling contains the technical descriptors symbolizing the voice of the organization.

Conformity of the product is ensured by considering engineering characteristics, design parameters and constraints. The relationship between customer requirements and technical descriptors are indicated over the house of quality. The roof of the house is for typing the correlation between technical descriptors. The similarities or oppositions between technical descriptors are defined in the roof of the house. The ground of the house is allocated for the prioritized technical descriptors. The rows for technical competitive assessment, degree of technical difficulty, target value, etc. are listed in the ground of the house.

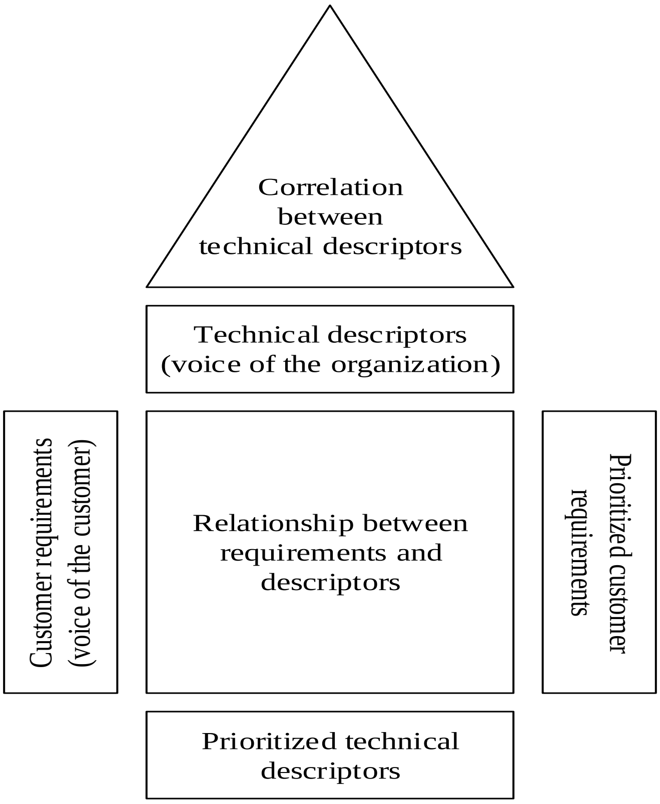

Figure 4.1 House of quality (Besterfield et al., 2003)

4.1.4 Conventional QFD Framework

House of quality is the framework matrix including all of the feature matrices required for the QFD method. It involves detailed information for the problem analysis, but it is important to remember that the parameter analysis is progressed until the reasonable amount of circumstances is obtained. The QFD process covers the deployment of HOQ through parts and assembly deployment, process planning and production planning as can be seen in Figure 4.2. The fundamental aim of the QFD analysis is to prioritize the ECs by using the information indicated in the HOQ.

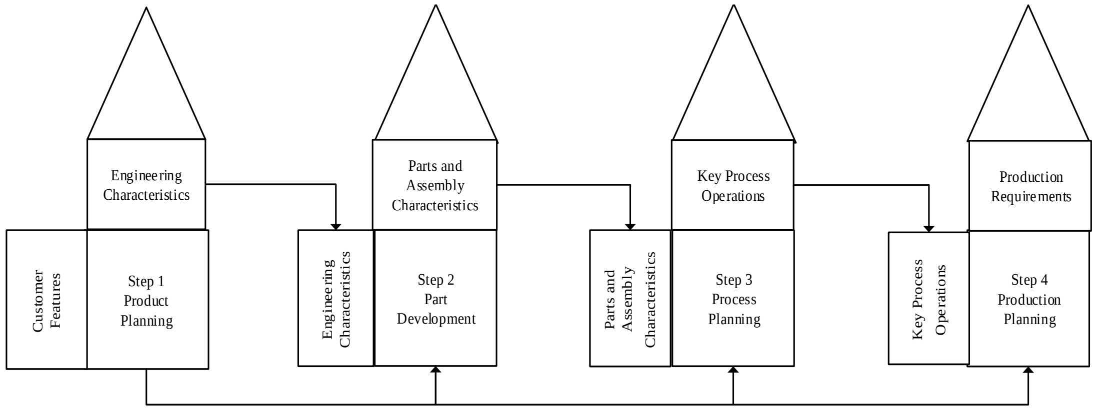

Figure 4.2 Deployment of HOQ in the QFD process (Kahraman et al., 2006)

The prioritized ECs are used as the substructure for giving important decisions in developing a new product.

4.1.5 The Planning and Deployment of a Quality Function

The information provided for QFD application is mostly limited and vague in practice. Furthermore, the information for QFD application is even more inaccurate for new product development studies.

The planning and deployment of a quality function consist of three main stages:

1. Customer features and demands are defined,
2. The characteristics of a product and a process are identified, and
3. The strategy to achieve a goal in relation to a product and a process is developed.

The planning and deployment of a quality function cause that a quality plan is consistently arranged. The strategy for designing a quality function is that it should be considered as a dynamic happening. As long as the progress is performed through a quality way, variability of the relationships between system inputs appears. Therefore, the strategy might need refreshing during its application over time because of the impacts of customer behaviors, rivals` features, new products and technologies, etc.

4.1.6 Hierarchical Framework

There are six stages of the suggested hierarchical framework to construct a fundamental for the system of group decision making. The hierarchical framework advances the planning of the improvement process.

The structure of the proposed framework with multiple stages is designed to be able to solve complicated problems. The first stage of this structure is pursued by following stages respectively till the final stage. The cause and effect relationships of the elements of lower and higher stages can be performed to separate a complicated problem into its parts. The suggested framework has the flexibility of moving on to either previous or next stage to apply what-if analysis, when the outcome of the present stage is insufficient.

4.1.6.1 First Stage: Voice of the Customer

Step 1: CRs are described by utilizing the VOC. CRs have fundamental functions in QFD and they should be properly identified. The CRs can be divided into groups, e.g., primary CRs, secondary CRs, etc. The methods used in this step are market research, questionnaires, qualitative analysis, concept engineering, etc. (Griffin & Hauser, 1993). Concept engineering includes methodologies for clarifying vogue ideas of customers to describe visible CRs to serve better the real customer needs (Ullman, 2003).

Step 2: The identified CRs can be classified into four groups, which are called as one dimensional, must-be, attractive and indifferent (Ullman, 2003). The degree of customer satisfaction depends on product`s functionality respecting to CRs (Han et al., 2001). Kano analysis is often used in this step. The descriptions given below are considered:

1. When there is a proportionality among product functionality and customer satisfaction, this is described as one-dimensional CRs. If the feature performance is better than customers’ expectation, customers’ satisfaction level will rise and the feature original importance will decrease for this reason. Otherwise, the feature original importance will improve accordingly. The difference between the feature performance and customers’ expectation is proportionate to the marginal change of the feature original importance (Geng & Chu, 2012).

2. Must-be CRs are known as the CRs leading to dissatisfaction when not covered and no satisfaction when covered. Must-be CR is the basic quality aspect considered by customers. If the feature performance is better than customers’ expectation, this situation will not contribute to the customers’ satisfaction level. Therefore, customers will be less careful about the feature and the feature original importance will lower very much. When the feature performance is worse than customers’ expectation, customers’ satisfaction level will drastically drop, customers will be more careful about the feature and the feature original importance will improve very much (Geng & Chu, 2012).

3. Attractive CRs are known as the CRs leading to dissatisfaction when not covered and satisfaction when covered. Customers` expectation with regards to attractive feature is generally not very high. If the feature performance is better than the customers’ expectation, customers will be inspired, but they will keep giving attention to the feature. This means that the feature original importance will drop a little. Otherwise, the feature original importance will rise a little (Geng & Chu, 2012).

4. Indifferent CR causes neither satisfaction nor dissatisfaction regardless of whether they have been covered or not.

Apart from the mentioned categories so far, the sub-groups of CRs can be increased or decreased regarding to the type of application field. In this study, the fourth category, which is called indifferent CRs, is omitted to reduce of the size of the first relationship matrix.

The Kano model is improved by Prof. Dr. Noriaki Kano and it represents the theory of both product development and customer satisfaction. The Kano model of customer satisfaction categorizes product features on the basis of how they are comprehended by customers and their impact on customer satisfaction (Ullman, 2003).

The Kano model is eligible for describing CRs, determining ECs, concept engineering and analyzing competitive products (Ullman, 2003).

Classification of CRs is helpful in QFD to render them manageable. It depends on the QFD designer to put CRs into groups. The descriptions given above are not compulsory to use in the QFD studies. It depends on the related case study to choose the classifications of CR. When the number of classifications of CR increases, the size of the matrix rises as well.

The classification of CRs helps to be aware of the degree of importance of CR for the future design studies and establishing their target values for using in the second stage. For example, must-be requirements generally should be satisfied before one-dimensional requirements in practice (Han et al., 2001).

Step 3: This step covers the prioritization of the CRs from the customers` angle of view. As, they need to be put in order by considering the degree of importance for the following analyses. With this way, the QFD analyzer pay more attention on more important CR to reduce the dimensionality of the QFD process. The QFD team can rank each CR with numbers from 1 to 10, which specify ratings from least important to the most important. The rating is higher, when the CR is more important. Importance ratings symbolize relative importance of each CR in terms of each other and it is sometimes a difficult process to assign to CRs degree of importance with the ratings from 1 to 10 (Besterfield et al., 2003). AHP can also be used in determining the degree of importance of CRs of a group of customers (Saaty, 1994).

4.1.6.2 Second Stage: Competitive Analysis

Step 1: CRs are benchmarked with the customers` way of thinking in the first step. An institution`s and its rivals` performances of quality are compared by considering each CR in QFD process. This creates a framework to arrange the targets on it. Then, it becomes possible to estimate which CR can provide better competitive advantages. Therefore, benchmarking is useful to explore operational and strategic opportunities (Han et al., 2001).

Step 2: Target values of each selected CRs are determined in the second step. At this step, each CR at a satisfactory fulfillment level is removed from further consideration. Then, the size of the matrix is consistently reduced. If the results of this stage is not as expected, the first stage can be restarted by the QFD analyzer to try to achieve better outcomes.

4.1.6.3 Third Stage: Voice of the Institution

The VOC is used to describe the voice of the institution in the third stage. The CRs are transformed to the ECs quantitatively in the QFD planning process. Concept engineering methodology can be useful for determining ECs (Han et al., 2001). As already mentioned previously, when the outcome of this stage does not meet the expectations, the QFD analyzer can return to either the first or the second stage.

4.1.6.4 Fourth Stage: Design Targets

Step 1: The crucial CRs are surely identified with measurable terms in the first step (Han et al., 2001). Then, the QFD analyzer is aware of considerable CRs for the future design studies. This step is almost the same as the first step of the second stage. However, the QFD analyzer can evaluate the capacity of institution in fulfilling the crucial CRs as well. The assessment and comparison of institution`s and competitors` crucial ECs are performed in this step.

Step 2: The target values of the ECs are indicated in the second step. The target values of the ECs and the target values of the CRs can be compared to understand whether the technical features are able to meet customer perceptions.

Step 3: The cost of the ECs to meet the target values of the CRs can be determined in the third step. The degree of technical difficulty, required time, etc., can also be reported as constraints in performing the target values of the CRs.

4.1.6.5 Fifth Stage: Relationship Matrix

Importance weights are just numerical indicators and they cannot guarantee that ECs meet customer needs. Therefore, different type of scales to measure the relationships between CRs and ECs are necessary to assure that customer needs are covered.

The HOQ is filled with the information of contribution of each EC to meet target level of each CR. The factors of positive, negative or no effect are put into the matrix. A profound understanding of ECs is necessary for its implementation to meet the target levels of CRs. The impact of the fulfillment of ECs on the satisfaction of CRs can be quantified.

The degree of relationship between a CR and an EC can be scaled as strong, medium, weak or no relationship. The grades can be chosen as 9, 3, 1 and 0 to from strong to no relationship degrees. They are used to calculate importance weights of ECs.

ECs are selected by utilizing their calculated importance weights. However, implementation of ECs might not be enough to catch the target levels of CRs.

4.1.6.6 Sixth Stage: Correlation Matrix

Step 1: The tradeoffs among the ECs are indicated in the first step. The change of an EC can have strongly positive, positive, negative, strongly negative or no effect on any other ECs. The assignment of positive or negative correlation depends on the influence of ECs on achieving other ECs. Positive correlation points out same direction of two ECs, whereas negative correlation indicates an adverse effect of two ECs to each other.

Step 2: ECs, which efficiently cover the CR by considering constraints, are chosen for the QFD planning process in the second step.

4.2 QFD Solution Method with Formulations

In the HOQ chart shown in Figure 4.3 below, the cell *(i, j)* of the relationship matrix of ECs and CRs represents the intersection of *i*th row and *j* th column of an HOQ chart, The cells of the relationship matrix of CRs and ECs, are assigned with the values of 1, 3 and 9 to represent a weak, medium and strong relationship respectively between CR_i, which is the *i*th CR, and EC_j, which is the *j*th EC. The importance value of an EC is calculated by utilizing both the CRs importance weights and the relationship coefficients assigned to the cells. The $ECIV_j$ value is calculated by using the following formula for each EC.

$$ECIV_j = \sum_{i=1}^{m} w_i * R_{ij} \tag{4.1}$$

where $j = 1, 2, \ldots, n$ and w_i is the importance weight of CR_i, $(i = 1, 2, \ldots, m)$ and R_{ij} is the relationship coefficient between CR_i and DR_j.

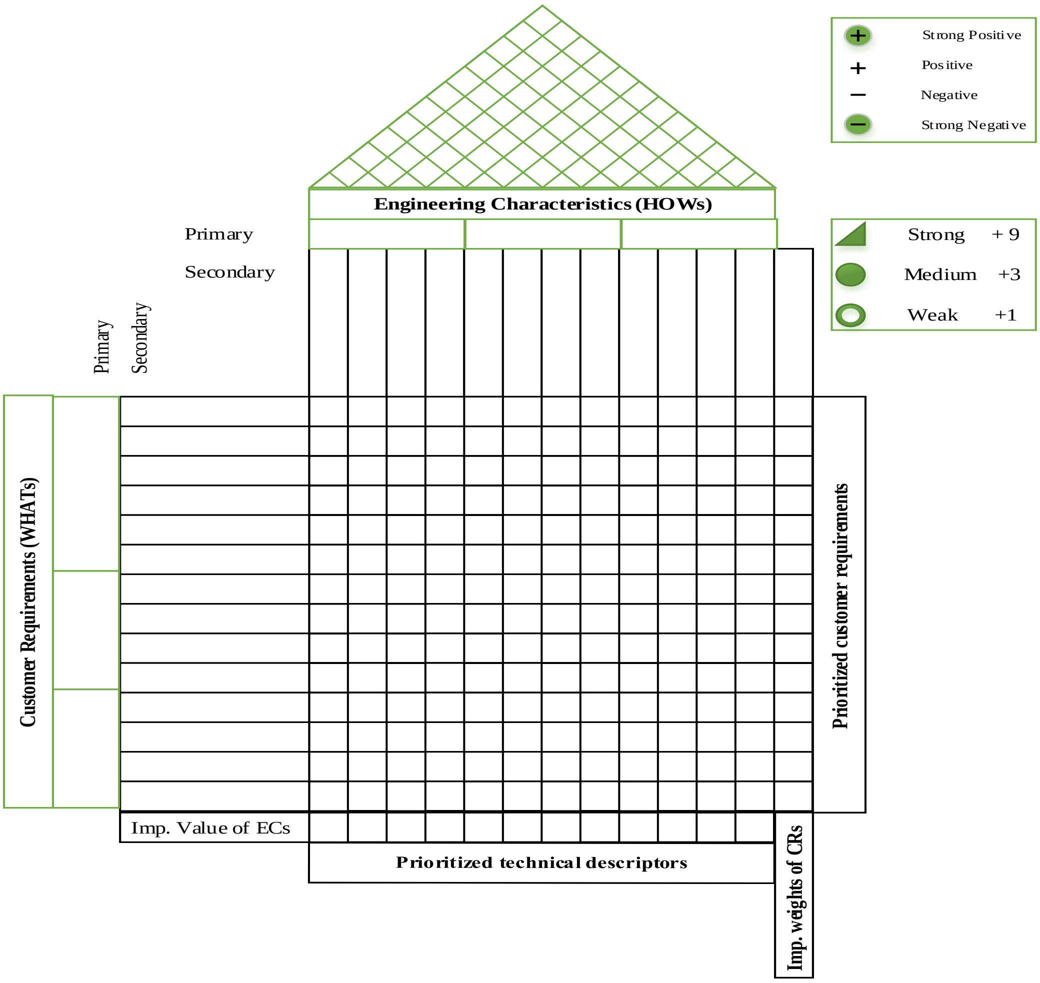

Figure 4.3 The framework of HOQ

The calculated $ECIV_j$ is recorded to its related cell over the HOQ shown in Figure 4.3. The vagueness of the human judgement is considered to find out more objective importance weights of CRs in this thesis. This imprecise ideas of engineering team members are defined by fuzzy numbers and their extent of contribution to the achievement of the goal is hierarchically researched in the thesis. In order to achieve this aim, fuzzy AHP with extent analysis approach is applied in the QFD for the calculation of importance weights of CRs.

4.3 Fuzzy AHP with an Extent Analysis Method and Its Formulations

Estimating the CRs` importance weights is basically important in QFD mechanism. Therefore, Kwong & Bai (2003) proposed a fuzzy AHP with an extent analysis approach to calculate the importance weights for the CRs. The proposed model was used in place of the conventional AHP approach determining weight vectors, which are not precise. Their approach was including fuzzy logic calculations. Since, human thinking was not precise and clear. Triangular fuzzy numbers were used for creating pairwise comparison matrices in their approach. Subsequently, the extent analysis method is used to calculate the CRs importance weight vectors.

A product's splash mostly based on how it meets CRs (Kwong & Bai, 2003). Calculating the correct importance weights for the CRs is crucial, because they explicitly influence the set of importance values for the ECs. The fundamental way of finding prioritized CRs is to rank them from 1 to 5 or 1 to 10 (Griffin & Hauser, 1993). However, this method is not able to precisely reveal human perception.

As stated by Saaty (1994), CRs are firstly grouped into the different hierarchical levels to prioritize the CRs by using the AHP. An affinity diagram or a tree diagram can be used to categorize the CRs into a hierarchical order.

4.3.1 Construction of Fuzzy Judgement Matrices

The hierarchy shown in Figure 4.4 is used by decision makers to calculate the relative importance values of the elements on a pairwise basis. The conventional AHP approach does not consider the uncertainty of human judgement. The pairwise comparison for the hierarchy of attributes (CRs) can be executed by using a five-point scale, such as, equally, moderately, strongly, very strongly or extremely (Kwong & Bai, 2003). The triangular fuzzy number method proposed by Chan et al. (1999) is applied to describe a pairwise comparison of CRs.

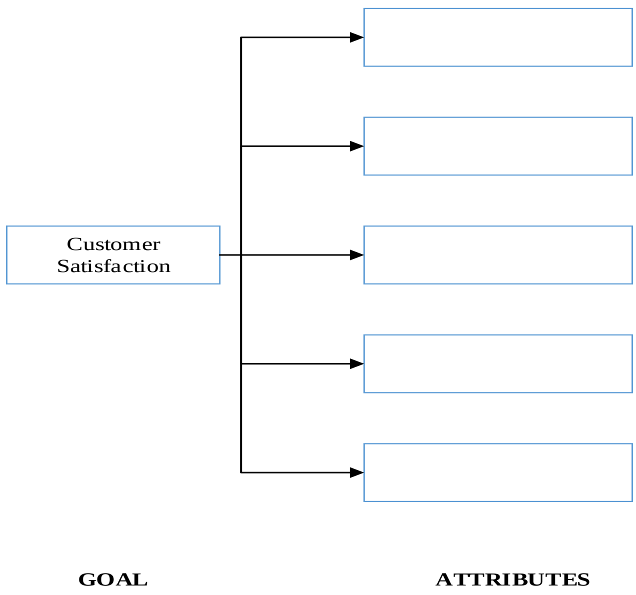

Figure 4.4 The hierarchy of customer requirements for the biogas product development

It is seen in Figure 4.4 that the CRs can be categorized with the one level of hierarchy for the customer satisfaction goal in a tree diagram.

4.3.2 Triangular Fuzzy Numbers

A fuzzy number is a fuzzy set $F = \{(x, \mu F(x)), x \in R\}$, where x takes its values on the real line R_1: $-\infty < x < +\infty$ and $\mu F(x)$ is a continuous plot from R_1 to the close interval [0, 1] (Kwong & Bai, 2003). A triangular fuzzy number can be symbolized as $M = (l, m, u)$. With reference to Kwong & Bai (2003), the membership function of a triangular fuzzy number is preesented as $\mu M(x)$: $R \rightarrow [0, 1]$ and is equal to:

$$\mu M(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l} \ ; \ x \in [l, m], \\ \frac{x}{m-u} - \frac{u}{m-u} \ ; \ x \in [m, u], \\ 0 \qquad ; otherwise \end{cases} \tag{4.2}$$

where $l \leq m \leq u$, l and u take place of the lower and upper value of the support of M, in order, and m is the middle value of M. When $l = m = u$, it is not a fuzzy number.

The fuzzy laws for adding, multiplying and finding inverse calculations for two triangular fuzzy numbers M_1 and M_2 are as follows (Kwong & Bai, 2003):

$$\text{Fuzzy Formulas} \begin{cases} M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2), \\ M_1 \otimes M_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2), \\ \lambda \otimes M_1 = (\lambda l_1, \lambda m_1, \lambda u_1), \lambda > 0, \lambda \in R, \\ {M_1}^{-1} \approx (1/u_1, 1/m_1, 1/l_1). \end{cases} \quad (4.3)$$

4.3.3 Fuzzy Representation of Assessment in a Pairwise Comparison of Customer Requirements

The human judgement is vague, so this vagueness can be considered for the determination of the pairwise comparison matrices of the CRs by using the triangular fuzzy numbers. Figure 4.5 presents the triangular fuzzy numbers M_t = (l_t, m_t, u_t) where $t = 1, 2 ... k$ and where l_t and u_t are the lower and upper values and m_t is the middle value of the fuzzy number M_t. δ symbolizes a fuzzy degree of judgement where $u_t - l_t = l_t - u_t = \delta$. A larger value of δ indicates a higher fuzzy degree of judgement. If $\delta = 0$, the judgement is not a fuzzy number. The value of δ was taken as 1 in this thesis.

4.3.4 Calculating The Consistency Index and Consistency Ratio

Saaty (1994) uses a consistency index (CI) to determine any inconsistency within the judgements in each comparison matrix as well as for the entire hierarchy in the AHP model. The CI is useful to understand whether or not the targets can be organized in an eligible order of ranking. The consistency of the pairwise comparison matrices can be also checked by CI (Kwong & Bai, 2003). The defuzzification method of triangular fuzzy numbers are used to find out the crisp matrices. When the fuzzy comparison matrices become crisp matrices, they are used to search for the consistency.

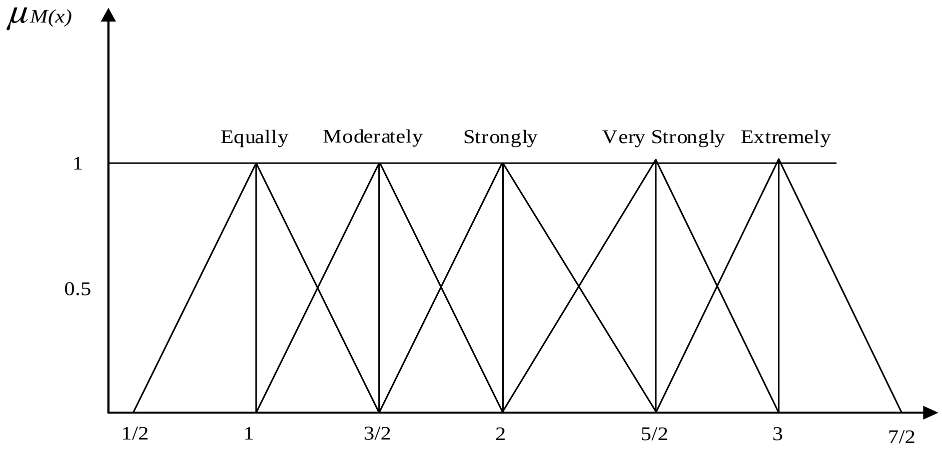

Figure 4.5 The membership functions of the triangular numbers

Saaty (1994) states that the values of the *CI* and the consistency ratio (*CR*) of a fuzzy comparison matrix can be calculated by using the equations hereunder:

$$CI = (\lambda_{max} - n)/(n - 1) \quad (4.4)$$

$$CR = (CI/RI(n)) * 100\% \quad (4.5)$$

where, λ_{max} is the largest eigenvalue of the fuzzy comparison matrix, *n* is the dimension of the matrix, and *RI* (n) is a random index. The random index is conditional to *n* and the RI values are shown in Table 4.1 (Kwong & Bai, 2003).

Table 4.1 Random index values depending on *n*

n	3	4	5	6	7	8	9
RI (n)	0.58	0.9	1.12	1.24	1.32	1.41	1.45

If the calculated *CR* of a comparison matrix is less than 10%, the consistency of the pairwise judgement is accepted. Otherwise, the judgments conveyed by the engineers are assumed to be inconsistent. Then, the pairwise comparison matrix is repeated.

By referencing Saaty (1994), the defuzzification of a triangular fuzzy number defined as $M = (l, m, u)$ can be executed to calculate its crisp value with the following formula:

$$M.crisp = (4m + l + u)/6 \quad (4.6)$$

4.3.5 Calculation of Weight Vectors for Individual Levels of a Hierarchy of the Customer Requirements

The extent analysis approach and the principles for the comparison of fuzzy numbers are applied to calculate the weight vectors of CRs (Chang, 1996). The satisfied extent of CRs to achieve the goal is determined by the extent analysis method. The extent is a fuzzy number. On the basis of the fuzzy values for the extent analysis of each object. A fuzzy synthetic degree value can be calculated by utilizing the fuzzy values of the hierarchy members by using the fuzzy extent analysis with Eq. (4.7) in reference to Chang (1996). Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set.

$$\sum_j^m M_{g_i}^j \otimes [\sum_i^n \sum_j^m M_{g_i}^j]^{-1} \quad (4.7)$$

where $M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^n$; $v \quad i = 1, 2, \ldots, n$, are triangular fuzzy numbers. Based on the above definition, the fuzzy synthetic degree values of all elements in the *k*th level can be calculated by using Eq. (4.7) on the basis of the fuzzy judgement matrix of the *k*th level in Eq. (4.8) as stated by Kwong & Bai (2003);

$$D_i^k = \sum_{j=1}^n a_{ij}^k \otimes [\sum_{i=1}^n \sum_{j=1}^m a_{ij}^k]^{-1}, i = 1, 2, \ldots, n \quad (4.8)$$

where D_i^k is the fuzzy synthetic degree values of element i in the *k*th level and $(a_{ij}^k)_{nn}$ is the fuzzy judgement matrix of the *k*th level.

4.3.6 Principles for the Comparison of Fuzzy Numbers

The principles allowing the comparison of fuzzy numbers are examined and formulated as stated by Zimmermann (1996) and Kwong & Bai (2003) in Eqs. (4.9) - (4.13) as followings:

Definition 1: M_1 and M_2 are two triangular fuzzy numbers. The degree of possibility of $M_1 \geq M_2$ is defined as:

$$V(M_1 \geq M_2) = sup_{x \geq y} [min(\mu M_1 (x), \mu M_2(y))] \quad (4.9)$$

Theorem 1: If M_1 and M_2 are triangular fuzzy numbers that are denoted by (l_1, m_1, u_1) and (l_2, m_2, u_2) respectively, then:

1. The necessary and sufficient condition of $V(M_1 \geq M_2) = 1$ is $m_1 \geq m_2$.
2. If $m_1 \leq m_2$, let $V(M_1 \geq M_2) = hgt(M_1 \cap M_2)$.

Then,

$$V(M_1 \geq M_2) = \mu(d) = \begin{cases} \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, & l_2 \leq u_1 \\ 0 & , otherwise \end{cases} \quad (4.10)$$

where d is the crossover point's abscissa for M_1 and M_2.

Definition 2: The degree of possibility for a fuzzy number to be greater than k fuzzy numbers M_i (i = 1, 2, . . . , k) can be defined by

$$V(M \geq M_1, M_2, \ldots, M_k) = min\ V(M \geq M_i),\ i = 1, 2, \ldots, k \quad (4.11)$$

Let $d(p_i^k) = min\ V(S_i^k \geq S_j^k)$, where, p_i^k is the ith element of the kth level, j = 1, 2, . . . , n; $j \neq i$. The number of elements in the kth level is n. Then the weight vector of the kth level is obtained as follows:

$$W'_k = (d(p_1^k), d(p_2^k), \dots, d(p_n^k))^T \tag{4.12}$$

The normalized weight vector, W_k is:

$$W_k = (w(p_1^k), w(p_2^k), \dots, w(p_n^k))^T \tag{4.13}$$

CHAPTER FIVE
CASE STUDY AND COMPUTATIONAL RESULTS

A QFD problem in wastewater treatment service sector is analyzed in this chapter of the thesis. A QFD model and a fuzzy AHP with an extent analysis approach are applied together in the wastewater treatment service sector.

5.1 Case Study

In recent years, most of the municipalities of the metropolitan cities in Turkey have had investments for adapting anaerobic sludge digestion systems into the wastewater treatment facilities. They aimed at providing better wastewater treatment service for the population and for having the ability of energy conversion at the same time. It is expected that initiating the adaptation of anaerobic digestion systems at wastewater treatment facilities in Turkey leads to rapid growing up of renewable energy use instead of fossil energy use as time goes by.

The HWTF is explained and detailed information about it is presented in the third chapter of the thesis. By considering the operations in HWTF, biogas product development problem in waste water treatment service sector is dealt in this section of the thesis.

The HOQ framework presented in Figure 4.3 is the main element of the QFD problem. In order to fill out the related HOQ, there are calculations to do by considering the QFD methodology and the fuzzy extent analysis method in accordance with each other.

As can be seen in Figure 4.4, the hierarchy of customer requirements for the biogas product development is considered as the first step. The estimated hierarchy is used both in the HOQ, pairwise and fuzzy comparison matrices. The goal is defined as biogas product development, while the customer requirements are chosen as energy efficiency (CR1), stability of content (CR2), purity (CR3), reliability (CR4) and affordability (CR5). The customer requirements can also be called attributes. They are used to achieve the goal of the hierarchy, which is the biogas product development.

The engineering team builds a pairwise comparison matrix, which includes triangular fuzzy numbers predicted by the members of the team. The engineering team includes three experienced engineers with different backgrounds. The fuzzy mapping used in the case study is indicated in Figure 4.5. Each participant must consider the related scale of fuzzy numbers to express their personal precedence. The pairwise comparison for attributes` category level is put in a matrix form as can be shown in Table 5.1. Eq. (4.3) is applied and the fuzzy comparison matrix for the related hierarchy level is obtained as presented in Table 5.2.

Table 5.1 Pairwise comparison for attributes

	CR1	CR2	CR3	CR4	CR5
CR1	(1, 1, 1)	(1/2, 1, 3/2) (1/2, 1, 3/2) (1, 3/2, 2)	(2/5, 1/2, 2/3) (1/3, 2/5, 1/2) (3/5, 1/2, 2/3)	(3/2, 2, 5/2) (3/2, 2, 5/2) (3/2, 2, 5/2)	(1/2, 1, 3/2) (1/2, 1, 3/2) (1/2, 2/3, 1)
CR2	(2/3, 1, 2) (2/3, 1, 2) (1/2, 2/3, 1)	(1, 1, 1)	(1/2, 1, 3/2) (1, 3/2, 2) (1/2, 1, 3/2)	(3/2, 2, 5/2) (3/2, 2. 5/2) (3/2, 2, 5/2)	(3/2, 2, 5/2) (1, 3/2, 2) (1, 3/2, 2)
CR3	(3/2, 2, 5/2) (2, 5/2, 3) (3/2, 2, 5/2)	(2/3, 1, 2) (1/2, 2/3, 1) (2/3, 1. 2)	(1, 1, 1)	(1, 3/2, 2) (3/2, 2, 5/2) (2, 5/2, 3)	(1/2, 1, 3/2) (1/2, 2/3, 1) (1/2, 1, 3/2)
CR4	(2/5, 1/2,2/3) (2/5, 1/2, 2/3) (2/5, 1/2, 2/3)	(2/5, 1/2, 2/3) (2/5, 1/2, 2/3) (2/5, 1/2, 2/3)	(1/2, 2/3, 1) (2/5, 1/2, 2/3) (1/3, 2/5, 1/2)	(1, 1, 1)	(1/3, 2/5, 1/2) (1/3, 2/5, 1/2) (1/3, 2/5, 1/2)
CR5	(2/3, 1, 2) (2/3, 1, 2) (1, 3/2, 2)	(2/5, 1/2, 2/3) (1/2, 2/3,1) (1/2, 2/3, 1)	(2/3, 1, 2) (1, 3/2, 2) (2/3, 1, 2)	(2, 5/2, 3) (2, 5/2, 3) (2, 5/2, 3)	(1, 1, 1)

Table 5.2 Fuzzy comparison matrix

	CR1	CR2	CR3	CR4	CR5
CR1	(1, 1, 1)	(0.66, 1.16, 1.66)	(0.44, 0.46, 0.61)	(1.5, 2, 2.5)	(0.5, 0.88, 1.33)
CR2	(0.6, 0.86, 1.51)	(1, 1, 1)	(0.66, 1.16, 1.66)	(1.5, 2, 2.5)	(1.16, 1.66, 2.16)
CR3	(1.64, 2.17, 2.27)	(0.6, 0.86, 1.51)	(1, 1, 1)	(1.5, 2. 2.5)	(0.5, 0.88, 1.5)
CR4	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(0.4, 0.5, 0.66)	(1, 1, 1)	(0.33, 0.4, 0.5)
CR5	(0.75, 1.13, 2)	(0.46, 0.6, 0.86)	(0.66, 1.13, 2)	(2, 2.5, 3.03)	(1, 1, 1)

Saaty (1994) elucidated that CI could be used to estimate any possible inconsistencies of the judgements in a fuzzy comparison matrix. Therefore, CI is used as an indicator of consistency of the fuzzy comparison matrix in the case study. The fuzzy comparison matrix is defuzzified by using Eq. (4.6). Then, the comparison matrix with crisp values are built as presented in Table 5.3.

Table 5.3 Comparison matrix

	CR1	CR2	CR3	CR4	CR5
CR1	1	1.16	0.481	2	0.891
CR2	0.925	1	1.16	2	1.66
CR3	2.099	0.925	1	2	0.92
CR4	0.51	0.51	0.51	1	0.405
CR5	1.212	0.62	1.197	2.505	1

The comparison matrix indicated in Table 5.3 is focused on for calculating its maximum eigenvalue. Then, λ_{max} is found out as 5.227. In regards to the random index values depending on *n* in Table 4.1, the related index value is chosen. Respecting to calculation by using Eqs. (4.4) and (4.5), the CI = 0.05675 and CR = 0.051 are calculated. In this case, it is estimated that $0.051 < 0.1$ and the consistency of the human judgement in the comparison matrix is consistent.

The CRs importance weights are calculated by using fuzzy extent method, before HOQ matrix is built. The fuzzy extent analysis method is used to research the satisfied extent of an object in order to achieve the goal.

The fuzzy synthetic degree value of each CR is calculated by considering the elements in the same row of the fuzzy comparison matrix with the related formulations. Eqs. (4.7) and (4.8) are used in this part of the calculations to find out the fuzzy synthetic degree values for each category.

The weight vector of each CR is calculated by considering Eqs. (4.9), (4.10) and (4.11) for the related definitions and theorem at the end of the fuzzy extent analysis approach. The minimum value in the weight vector of each CR category is chosen. Then, related weight values are normalized and the weight vector of CRs is attained as presented inside the brackets in Figure 5.1.

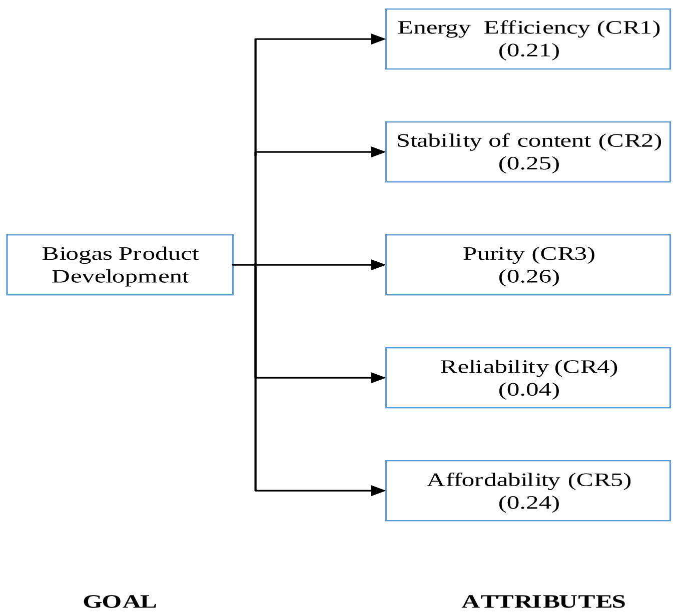

Figure 5.1 Importance weights of CRs in the hierarchy

Table 5.4 ECs importance values

Engineering Characteristics (ECs)											
Energy Phase				Infrastructure Req.				Process Requirement			
Natural gas	Liquefied gas	Compressed gas	Purified gas	Cryogenic storage	High pressure tank	Low pressure tank	Pipe line system	Absorption	Membrane	Cryogenic	Chemical Solution
4.44	7.08	2.92	8.68	0.99	2.83	1.29	3.15	6.52	6.6	6.6	6.84
Importance value of each EC ($ECIV_j$)											

The weights of CRs are placed into the corresponding cells of the HOQ matrix. The values of relationship scales of CRs and ECs in the HOQ matrix for the CRs are multiplied with the importance weights of the related CR and added to one another by considering Eq. (4.1) to find out the importance value of each EC, which is $ECIV_j$. The list of ECs along with the calculated importance values are presented in Table 5.4. Finally, the HOQ is built and presented in Figure 5.2, after all of these calculations.

5.2 Computational Results

The QFD model and fuzzy AHP with extent analysis approach are applied to a biogas product improvement problem in the wastewater treatment service industry to improve the characteristics of biogas by considering VOC and carrying on till the customer satisfaction is achieved. Biogas product development is identical to customer satisfaction. Since, the engineering team expect to sort out the quality and cost of energy problem in the wastewater treatment facility. The related details of the biogas product development is explained in chapter three. It can be remembered that the cost of energy outsourcing has a big rate in the budget and also quality problems of biogas lead to damage in the equipment and very high maintenance costs. Therefore, the factors influencing the biogas product development goal are determined and put into the tree diagram. In order to explain the effectiveness and capability of proposed model, computational results of an example is explained in this chapter.

The methodology starts with the QFD framework building, which includes CRs, on the left wall, ECs at the ceiling, the relationship matrix between ECs and CRs, the importance weight vector of CRs on the right wall, and ECs vector of importance weights at the ground of the house of quality. The roof of the house of quality is also available and it involves the correlation matrix of ECs. The HOQ matrix including the computational results of the case study is illustrated in Figure 5.2.

The relationship matrix is assigned with the values of 9, 3 and 1 for strong, medium and weak relationship, respectively and it shows the degree of relation between ECs and CRs. This part of the HOQ is very important. Since, this matrix is used for the calculation of the importance values of ECs. The relationship matrix is constructed by the engineering team as stated in Figure 5.2.

The correlation matrix for defining the internal relationship between ECs is placed at the roof of the HOQ. The correlations between ECs are researched with the degrees from strong negative to strong positive in the roof of the HOQ. With this part of the HOQ, it is possible to find which ECs support each other or mutually contradict to each other. This step is crucial for the consistent development of the HOQ.

Contradiction between ECs signs that CRs are in confliction. However, there is not any ECs correlation with negative or strong negative relation. Therefore, it is determined that the CRs do not conflict with each other, there is not any tradeoff between them and the fulfillment of CRs can be achieved with the present content of the HOQ in the case study.

The importance weight vector for the CRs is calculated with the fuzzy extent analysis approach. The normalized importance weight vector of CRs is found out as $W_k = (0.21, 0.25, 0.26, 0.04, 0.24)^T$. The highest importance value is for purity with 0.26, while the smallest importance weight value is for reliability with 0.04. However, energy efficiency with 0.21, stability of content with 0.25 and affordability with 0.24 are established with very close values to the weight value of purity. On the other hand, the importance values of the ECs are also calculated as 4.44, 7.08, 2.92 and 8.68 for the energy phase, 0.99, 2.83, 1.29 and 3.15 for the infrastructure requirement, 6.52, 6.6, 6.6 and 6.84 for the process requirement in order. As for the energy phase level, the biggest ECs values are found as 8.68 for purified biogas and 7.08 for liquefied gas. Related to the process requirement level, the largest ECs values are estimated as 3.15 for pipeline system and 2.83 for high pressure tank. By considering the process requirement level, the highest ECs values are determined as 6.84 for chemical solution and 6.6 for both cryogenic and membrane technologies. The CRs are fulfilled with the application of the ECs with the highest importance value at first.

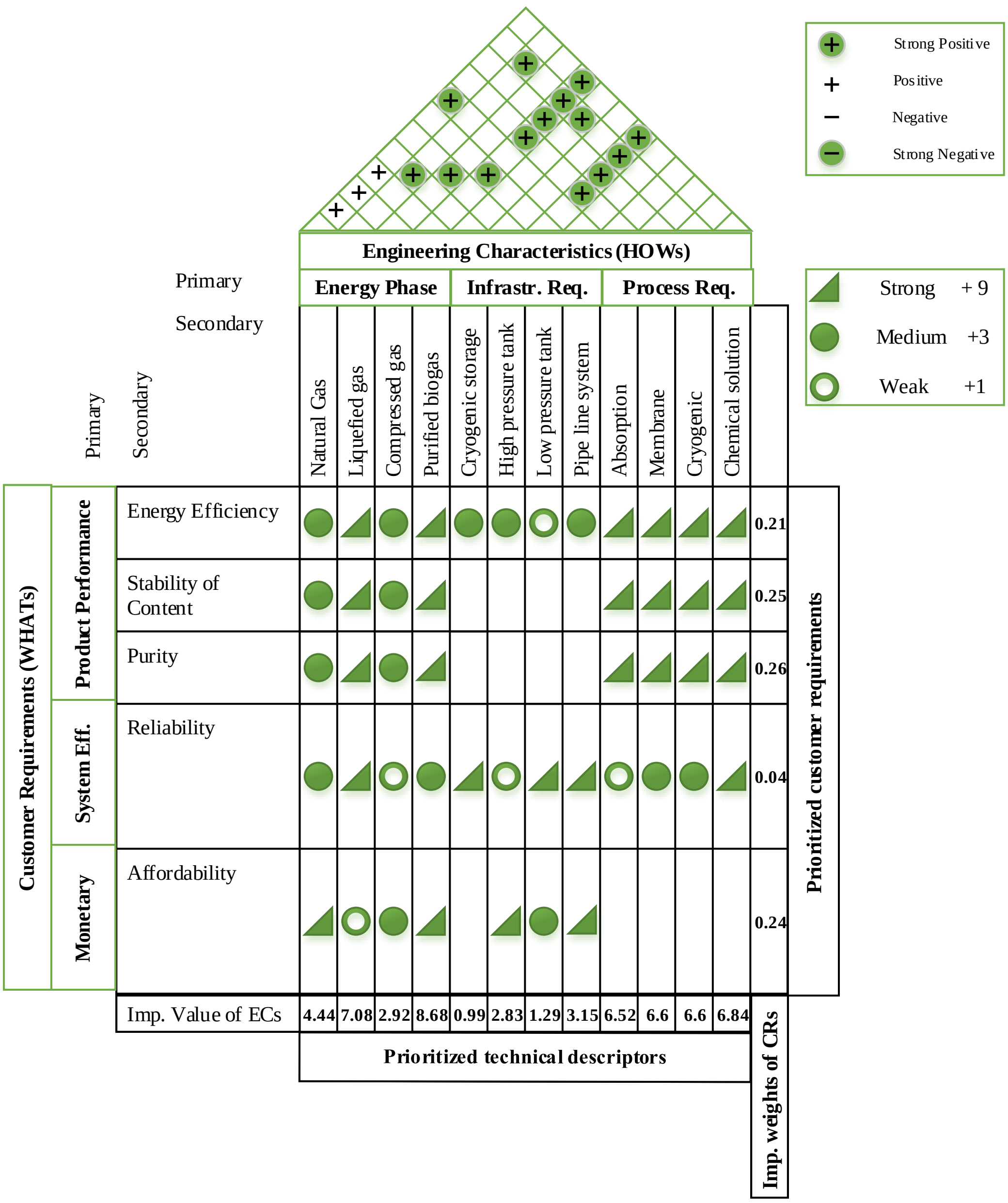

Figure 5.2 HOQ for the case study

The interpretations about the CRs of the engineering team from the HOQ of the case study in Figure 5.2 can be as followings:

1. The purity requirement of the energy source has the highest importance weight with 0.26.
2. The CRs are fulfilled by using the energy source in purified gas form, by providing the infrastructure for the pipeline system and by applying the related process for the chemical solution use.

3. The use of biogas at the HWTF should be supported with a consistent purification technology. Chemical solutions are already used in a scrubber to remove H_2S content of the biogas, but the present scrubber performance is not as developed as required to achieve the consistent biogas purity. The system can be overhauled and equipped with new technologies. CO_2 content, water vapor and siloxanes must be also removed from the content of biogas to achieve the required level of purification. The details of the new technologies for biogas upgrading are presented in sections 4.4 and 4.5 in detail.
4. The pipeline system for the purified biogas can be an efficient technology. However, the harmful content of the biogas, which covers CO_2, H_2S, water vapor and siloxanes, must be cleared to improve biogas quality. The infrastructure of the pipeline system to carry biogas in the HWTF and to any other users in neighbor areas can be provided to satisfy the CRs, after the efficient and proper run of the biogas purification process is achieved.

CHAPTER SIX
CONCLUSIONS

QFD, which is a methodology providing increased customer satisfaction along with lowered product improvement time and costs, has been widely admitted by prestigious corporations all around the world.

In this thesis, biogas product development problem in waste water treatment service industry is studied. An integrated solution methodology on the basis of QFD method and fuzzy extent analysis approach with the framework of the HOQ matrix is presented to address the biogas product development problem in wastewater treatment service industry. The needs of a public corporation and demands of the engineering team have motivated this study.

It has been stated that the calculation of importance values of the ECs from the classical QFD may be false. As, it does not pay attention to the vagueness of the human ideas and it can lead to unfavorable decisions of the analyzer and misleading inputs in the HOQ matrix. In fact, classical QFD approach may not be sensitive to the variation of importance values of CRs.

An attempt has been made to test the applicability of QFD as a decision-making tool to estimate the best strategy to achieve the goal of biogas product development in wastewater treatment service industry. It is seen that the determination of the importance weights of CRs is the misleading characteristic of classical QFD method. The ECs are also analyzed with the calculation of their importance values by using the weight values of CRs. Therefore, importance weight prediction of CRs under uncertain human behaviors and ideas implicitly influence the weight values of ECs. Furthermore, estimation of the importance weights of CRs involves subjectivity with a large extent. Therefore, fuzzy extent analysis approach is used for the calculation of the importance weights of CRs in the related case study. Moreover, it is found out that fuzzy extent analysis approach functions to tolerate the weaknesses of the classical QFD method in uncertain conditions.

The QFD analysis, which is supported with the fuzzy logic calculations and fuzzy extent analysis approach, is presented. The biogas product development problem at wastewater treatment service industry is analyzed. The purity is found out as the most important CR, whereas reliability is chosen as the least important CR. Stability of content, affordability and energy efficiency have taken their importance weights in descending order and lower than the importance weight of purity. However, their importance weights are larger than the importance weight of reliability. The LNG is determined as the best alternative energy for purified biogas. In addition, NG and CNG are the last two energy sources in the gas phase. Related to the infrastructure requirements, high pressure tanks are selected in the second place following to the pipeline system in the first place. Process requirements are satisfied by using chemical solutions for purification process with the highest importance value. The second choice can be either membrane or cryogenic process. Absorption process is another and the last option, although there is not a big gap between its importance value and others` importance values.

The QFD application in the case study results in by recommending that the CRs at the wastewater treatment service industry for biogas development problem can be covered firstly by choosing purified gas as the energy source; secondly, by ensuring the infrastructure for the pipeline system conditionally upon reaching at the global purification standards of biogas at the wastewater treatment facility and thirdly, by installing the needed technology to achieve the process requirements for the chemical solution use in biogas purification.

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